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GOES-R Advanced Baseline Imager (ABI) Algorithm Theoretical Basis Document For Low Cloud and Fog

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LIST OF ACRONYMS

ABI – Advanced Baseline Imager
AC – Above Cloud
ACT – ABI Cloud Type
AGL – Above Ground Level
ASOS – Automated Surface Observing System
AIADD – Algorithm Interface and Ancillary Data Description
ARM – Atmospheric Radiation Measurement
ATBD – Algorithm Theoretical Basis Document
AVHRR – Advanced Very High Resolution Radiometer
BT – Brightness Temperature
CALIOP – Cloud-Aerosol Lidar with Orthogonal Polarization
CALIPSO – Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation
CDF – Cumulative Distribution Function
CONUS – Continental United States
DOD – Department of Defense
EOS – Earth Observing System
ESA – European Space Agency
F&PS – Functional & Performance Specification
FAA – Federal Aviation Administration
FAR – False Alarm Rate
GOES – Geostationary Operational Environmental Satellite
KSS – Hanssen-Kuiper Skill Score
LRC – Local Radiative Center
LUT – Look-up Table
MODIS – Moderate Resolution Imaging Spectroradiometer
NASA – National Aeronautics and Space Agency
NESDIS – National Environmental Satellite, Data, and Information Service
NOAA – National Oceanic and Atmospheric Administration
NWP – Numerical Weather Prediction
NWS – National Weather Service
POD – Probability Of Detection
POES – Polar Operational Environmental Satellite
PQI – Product Quality Information
QF – Quality Flag
SEVIRI – Spinning Enhanced Visible and Infrared Imager
SODAR – Sonic Detection And Ranging
SSEC – Space Science and Engineering Center
STAR – Center for Satellite Applications and Research
TOA – Top of Atmosphere

ABSTRACT

This document provides a high level description of the physical basis of the fog/low cloud detection algorithm for the Advanced Baseline Imager (ABI), flown on the GOES-R series of NOAA geostationary meteorological satellites. The GOES-R fog/low cloud detection product is designed to quantitatively identify clouds that produce Instrument Flight Rules (IFR) conditions, defined as having a cloud ceiling between 500 ft (152 m) and 1000 ft (305 m) above ground level (AGL), or Low Instrument Flight Rules (LIFR) conditions, defined as having a cloud ceiling below 500 ft (152 m) AGL. The GOES-R fog product does not differentiate between IFR and LIFR conditions, but rather returns a probability that the cloud ceiling is below 1000 ft (305 m) AGL. There are visibility requirements included in the IFR and LIFR definitions; however, surface visibility is not available for the GOES-R algorithm (the GOES-R surface visibility algorithm relies on the fog product described herein) and is therefore not used for the GOES-R fog/low cloud algorithm. At night, the algorithm utilizes the 3.9 and 11 μm channels to detect IFR conditions. Fog detection during the day is determined using the 0.65, 3.9, and 11 μm channels. The fog detection algorithm utilizes textural and spectral information, as well as the difference between the cloud radiative temperature and surface temperature.

There are a few important caveats that users need to be aware of. Fog cannot be detected if there are higher cloud layers overlaying the fog layer. The GOES-R fog/low cloud product specifications reflect this fundamental limitation of passive remote sensing. Secondly, passive satellite measurements do not provide direct information on cloud base or ceiling, so the properties of the cloud layer actually sensed by the radiometer must be used to indirectly infer information on cloud base. Since the properties of the cloud base are not directly measured, variations in cloud base due to local boundary layer effects (e.g. local moisture sources/sinks and local turbulent mixing processes) generally will not be captured. Also, limited spatial resolution and errors in forecast model temperature data may make accurate fog/low cloud detection difficult in mountainous regions due to underlying terrain that may not be accurately accounted for. As such, not every surface observation underneath a GOES-R detected low cloud will necessarily indicate a ceiling of 1000 ft AGL or lower, but those surface observations that do not indicate LIFR or IFR will generally indicate Marginal Visual Flight Rules (MVFR) conditions, defined as having a cloud ceiling between 1000 ft (305 m) and 3000 ft (1515 m) AGL. In other words, the GOES-R fog/low cloud algorithm will rarely identify Visual Flight Rules (VFR) conditions, which is desirable.

The GOES-R fog/low cloud detection algorithm is required to achieve a skill score (probability of detection – probability of false alarm) of 0.70. Validation efforts indicate the algorithm is close to meeting this specification.

INTRODUCTION

1.1 Purpose of This Document

The fog/low cloud detection algorithm theoretical basis document (ATBD) provides a high level description of the physical basis for detecting low cloud and fog, which produces Instrument Flight Rules (IFR) conditions, with images taken by the Advanced Baseline Imager (ABI) flown on the GOES-R series of NOAA geostationary meteorological satellites. IFR conditions occur when the cloud base is 305 m (1000 ft) above ground level (AGL) or lower or surface visibility is less than 3 miles. Surface visibility is not available to the GOES-R fog/low cloud algorithm (the GOES-R surface visibility algorithm relies on the fog product described herein) so for this algorithm IFR conditions are defined as just having a ceiling less than 305 m (1000 ft) AGL. The fog/low stratus algorithm (herein called the fog algorithm) provides a binary mask, which indicates the presence or absence of fog/low cloud (IFR conditions) as well as fog/low cloud thickness within each ABI pixel.

1.2 Who Should Use This Document

The intended users of this document are those interested in understanding the physical basis of the fog algorithm. This document also provides information useful to anyone maintaining or modifying the original algorithm.

1.3 Inside Each Section

This document is broken down into the following main sections.

- **System Overview**: Provides relevant details of the ABI and provides a brief description of the products generated by the algorithm.

- **Algorithm Description**: Provides all the detailed description of the algorithm including its physical basis, its input and its output.

- **Test Data Sets and Outputs:** Provides a detailed description of the data sets used to develop and test the GOES-R ABI algorithm and describes the algorithm output.

- **Practical Considerations:** Provides a description of algorithm programming and quality control considerations.

- **Assumptions and Limitations**: Provides an overview of the current limitations of the approach and gives the plan for overcoming these limitations with further algorithm development.

1.4 Related Documents

- GOES-R Functional & Performance Specification Document (F&PS)
- GOES-R ABI Fog/Low Cloud Detection Validation Plan Document
- Algorithm Interface and Ancillary Data Description (AIADD) Document

1.5 Revision History

- 9/30/2009 - Version 0.1 of this document was created by Corey Calvert (UW-CIMSS). Version 0.1 represents the first draft of this document.

- 7/31/2010 – Version 1.0 of this document was created by Corey Calvert (UW-CIMSS) and Michael Pavolonis (NOAA/NESDIS). In this revision, Version 0.1 was revised to meet 80% delivery standards.

- 9/15/2010 – Version 1.0 of this document was revised by Corey Calvert (UW-CIMSS) and Michael J Pavolonis (NOAA/NESDIS/STAR). In this revision, Version 1.0 was revised based on reviewer comments.

OBSERVING SYSTEM OVERVIEW

This section describes the products generated by the ABI fog algorithm and the requirements it places on the sensor.

1.6 Products Generated

The fog algorithm is responsible for detecting fog/low clouds (those that produce Instrument Flight Rules (IFR) Conditions) and estimating its geometric thickness. The fog product requirements state that a binary mask indicating the presence or absence of fog be produced, along with an estimate of the geometric thickness of the fog (fog depth).

1.6.1 Product Requirements

The F&PS requirements for fog/low cloud are listed in Table 1.

Table 1: F&PS requirements for GOES-R fog/low cloud products.

Name	Low Cloud and Fog
User & Priority	GOES-R
Geographic Coverage	FD (full disk)
Temporal Coverage Qualifiers	Day and Night
Product Extent Qualifier	Quantitative out to at least 70 degrees LZA and qualitative beyond
Cloud Cover Conditions Qualifier	Clear conditions down to feature of interest (no high clouds obscuring fog) associated with threshold accuracy
Product Statistics Qualifier	Over low cloud and fog cases with at least 42% occurrence in the region
Vertical Resolution	0.5 km (Depth)
Horizontal Resolution	2 km
Mapping Accuracy	1 km
Measurement Range	Fog/No Fog

Measurement Accuracy	70% Correct Detection
Refresh Rate/Coverage Time Option (Mode 3)	15 min
Refresh Rate Option (Mode 4)	5 min
Data Latency	159 sec
Long-Term Stability	TBD
Product Measurement Precision	Undefined for binary mask

1.7 Instrument Characteristics

The fog algorithm will be applied to each earth located ABI pixel with valid L1b data. Table 2 summarizes the channels used by the fog algorithm. Even though the fog algorithm directly utilizes only a few channels, it indirectly utilizes many more ABI channels through its dependence on the ABI cloud mask, cloud phase, and daytime optical properties products.

Channel Number	*Wavelength (μm)*	*Used in Fog Detection*
1	0.47	
2	0.64	✓
3	0.86	
4	1.38	
5	1.61	
6	2.26	
7	3.9	✓
8	6.15	
9	7.0	
10	7.4	
11	8.5	
12	9.7	
13	10.35	
14	11.2	✓
15	12.3	
16	13.3	

Table 2: Channel numbers and wavelengths for the ABI.

The fog algorithm relies on spectral tests and is therefore sensitive to any imagery artifacts or instrument noise. Due to the use of other cloud algorithms, any instrument-related artifacts, which impact the cloud mask, cloud phase or cloud optical properties may impact the fog algorithm. The channel specifications are given in the F&PS section 3.4.2.1.4.0. We are assuming the performance outlined in the F&PS during our development efforts.

ALGORITHM DESCRIPTION

This section offers a complete description of the fog algorithm at its current level of maturity (which will improve with each revision).

1.8 Algorithm Overview

The GOES-R fog/low cloud algorithm is designed to quantitatively identify clouds that produce Instrument Flight Rules (IFR) conditions, defined as having a cloud ceiling between 500 ft (152 m) and 1000 ft (305 m) above ground level (AGL), or Low Instrument Flight Rules (LIFR) conditions, defined as having a cloud ceiling below 500 ft (152 m) AGL. The GOES-R fog product does not differentiate between IFR and LIFR conditions, but rather returns a probability that the cloud ceiling is below 1000 ft (305 m) AGL. There are visibility requirements included in the IFR and LIFR definitions; however, surface visibility is not available for the GOES-R algorithm (the GOES-R surface visibility algorithm relies on the fog product described herein) and is therefore not used for the GOES-R fog/low cloud algorithm. At night, the algorithm utilizes the 3.9 and 11 μm channels to detect IFR conditions. Fog detection during the day is determined using the 0.65, 3.9, and 11 μm channels. The fog detection algorithm utilizes textural and spectral information, as well as the difference between the cloud radiative temperature and surface temperature. The fog detection scheme is probabilistic in nature and utilizes advanced spatial analysis (cloud object analysis) to minimize false positive results. At night, the fog geometric thickness (fog depth) is estimated using a 3.9 μm based empirical relationship. During the day, fog depth is calculated using the ABI cloud Liquid Water Path (LWP) product and an assumption regarding the vertical distribution of cloud water.

The ABI fog detection algorithm derives the following products listed in the F&PS
- Fog detection (a yes/no binary mask)
- Fog depth (the geometric thickness of the fog layer)

Both of these products are derived at the pixel level.

In addition, the fog detection algorithm derives the following products that are not included in the F&PS.
- Quality Flags (defined in section 1.12.1.1)
- Product Quality Information (defined in section 1.12.1.2)
- Metadata (defined in section 1.12.1.3)

1.9 Processing Outline

As discussed earlier, the fog algorithm is dependent on several cloud products. Thus, prior to calling the fog algorithm, the ABI cloud mask, cloud phase, and daytime cloud optical properties must be generated. While the fog algorithm does not directly utilize output from the ABI cloud height algorithm, the daytime optical properties algorithm does depend on the cloud height output. As such, the algorithm processing precedence required to generate the fog products is as follows: ABI cloud mask → ABI cloud phase/type → ABI cloud height → ABI daytime microphysical properties → ABI fog detection. The fog detection algorithm requires at least 3 scan lines of ABI data due to the spatial analysis that is utilized in the algorithm. The processing outline of the fog detection algorithm is summarized in Figure 1.

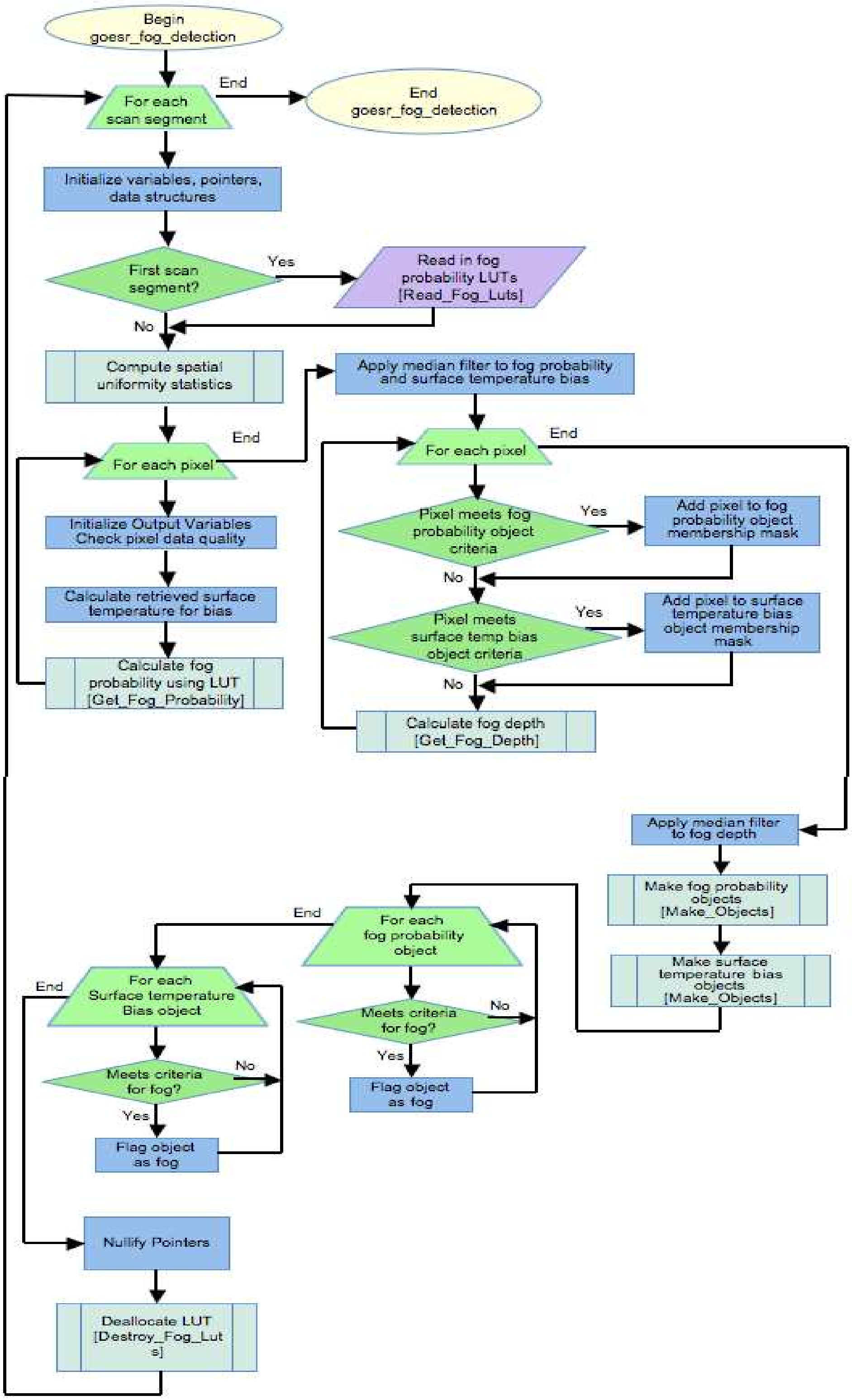


Figure 1 - High-level flowchart of the fog algorithm illustrating the main processing sections.

1.10 Algorithm Input

This section describes the input needed to process the fog algorithm. While the fog products are derived for each pixel, the use of spatial information requires knowledge of the surrounding pixels. In its current operation, the fog algorithm runs on segments of 200 scan-lines, but a minimum of 3 scan lines are required by the spatial analysis routines.

1.10.1 Primary Sensor Data

The lists below contain the primary and derived sensor data used by the fog algorithm. By primary sensor data, we mean information that is derived solely from the ABI observations and geolocation information.

- Calibrated reflectances for ABI channels 2 (0.65 μm) and 7 (3.9 μm)
- Calibrated radiances for ABI channels 7 (3.9 μm) and 14 (11 μm)
- Calibrated brightness temperature for ABI channel 14 (11 μm)
- L1b quality information from calibration for ABI channels 2, 7, and 14
- Space mask (is the pixel geolocated on the surface of the Earth?)
- Solar zenith angle

1.10.2 Derived Data

The following upstream ABI derived products are needed by the fog algorithm.

- ABI cloud mask output (product developed by cloud team)
- ABI cloud phase output (product developed by cloud team)
- ABI cloud Liquid Water Path (LWP) (product developed by the cloud team)

1.10.3 Ancillary Data

The following data lists and briefly describes the ancillary data required to run the fog algorithm. By ancillary data, we mean data that requires information not included in the ABI observations or geolocation data.

- **Surface emissivity of ABI channels 7 (3.9 μm) and 14 (11 μm)**
  A global database of monthly mean infrared land surface emissivity is required for ABI channels 7 and 14. The fog algorithm utilizes surface emissivity derived using the Moderate Resolution Imaging Spectroradiometer (MODIS). Emissivity is available globally at ten wavelengths (3.6, 4.3, 5.0, 5.8, 7.6, 8.3, 9.3, 10.8, 12.1, and 14.3 microns) with 0.05 degree spatial resolution (Seemann et al. 2008). The

ten wavelengths serve as anchor points in the linear interpolation to any wavelength between 3.6 and 14.3 microns. The monthly emissivities have been integrated over the ABI spectral response functions to match the ABI channels. This data set and the procedure for spectrally and spatially mapping it to the ABI are described in detail in Seemann et al. (2008) and the AIADD Document.

- **Surface temperature**
  Relative to other cloud types, fog has a very similar temperature as the surface. In order to identify clouds that have a similar temperature as the surface, surface temperature information from a Numerical Weather Prediction (NWP) model is required. While six-hour forecasts were used in the development of the fog detection algorithm, and, as such, are recommended, any forecast in the 0 to 24 hour range is acceptable. Details concerning the NWP data can be found in the AIADD Document.

1.10.4 Radiative Transfer Models

The following lists and briefly describes the data that must be calculated by a radiative transfer model and derived prior to running the fog detection algorithm. See the AIADD Document for a more detailed description.

- **Clear sky transmittance profiles for channels 7 and 14**
  The fog detection algorithm requires a profile of clear sky transmittance, where the transmittance at a given level in the profile is the upwelling clear sky transmittance integrated from that level to the top of the atmosphere.

- **Clear sky radiance profiles for channels 7 and 14**
  The fog detection algorithm requires a profile of clear sky radiance, where the radiance at a given level in the profile is the upwelling clear sky radiance integrated from that level to the top of the atmosphere.

1.11 Theoretical Description

Fog and low stratus detection is the process of determining which pixels contain clouds with bases below 305 m (1000 ft), where aviation Instrument Flight Rules (IFR) are in effect. The thickness of the fog/cloud is the vertical distance between the cloud base and the cloud top. The channel combination used to detect fog depends on the solar zenith angle. At night, the ABI fog detection algorithm directly utilizes the 3.9 (ABI channel 7) and 11 μm (ABI channel 14) channels. During the day, the fog detection algorithm directly utilizes the 0.65 (ABI channel 2), 3.9 (ABI channel 7), and 11 μm (ABI channel 14) channels. The central wavelength of each ABI channel will be used throughout this document in lieu of ABI channel numbers.

1.11.1 Physics of the Problem

Fog has the following physical properties (among others) (e.g. Pruppacher and Klett, 1997; Rogers and Yau, 1989).

- Composed mainly of liquid water
- Low cloud base
- Fog layers are highly spatially uniform in both temperature and reflectance since vertical velocities are typically weak
- Fog has a similar temperature as the surface
- Fog is generally composed of small droplets due to the high concentration of cloud condensation nuclei in the boundary layer and reduced collision/coalescence processes
- Low water content (primarily due to low vertical velocities).

The above physical properties allow fog to be differentiated from other cloud types (when fog is the highest cloud layer) using a combination of visible, near-infrared, and infrared observations from passive satellite sensors like the ABI. For instance, a common method for detecting fog/low cloud at night involves using the blackbody temperature difference between the 11- and 3.9-μm brightness temperatures on a variety of instruments (Eyre et al. 1984; Turner et al. 1986; Ellrod 1995; Lee et al. 1997; Bendix 2002). Ellrod (2003) also used the difference between the 11 μm temperature and surface temperature at night to estimate the probability that cloud base heights were below 1000 ft, the threshold for IFR. Daytime fog detection is trickier due to solar contamination of the 3.9 μm channel. Cermak and Bendix (2008) address this problem by using spatial metrics and the microphysical properties of clouds to estimate cloud thickness and height to detect fog/low cloud during the day for both MODIS and SEVIRI. The final algorithm for the ABI will be a quantitative, probabilistic algorithm based on common fog detection methods with a new object-based methodology that can be used during both day and night.

1.11.2 Mathematical Description

These subsections describe in detail how the fog detection algorithm is implemented. Firstly, the metrics used to determine if fog is potentially present are described. Next, the use of cloud objects is described, followed by a description of the fog/no fog decision tree.

It is important to note that the methodology used to detect fog is solar zenith angle dependent. At solar zenith angles < 90^o, the daytime methodology is used. The nighttime methodology is used when the solar zenith angle > 90^o.

1.11.2.1 Fog Property Metrics

A series of radiometric and textural metrics are used to determine which, if any, of the physical properties of fog are present. These metrics are described in the following sections.

1.11.2.1.1 *The 3.9 μm Pseudo-emissivity*

The 3.9 – 11 μm brightness temperature difference (BTD(3.9-11 μm)) has been traditionally used to identify potential areas of fog/low cloud (e.g. Ellrod 1995). In lieu of the BTD(3.9-11 μm), we utilize the 3.9 μm pseudo-emissivity (ems(3.9 μm)) shown in Equation 1. The 3.9 μm pseudo-emissivity is simply the ratio of the observed 3.9 μm radiance (numerator) and the 3.9 μm blackbody radiance calculated using the 11 μm brightness temperature (denominator). In Equation 1, BT is "brightness temperature" and B is the Planck Function. The 3.9 μm pseudo-emissivity is preferred over the BTD(3.9-11 μm) because it is less sensitive to the scene temperature. The ems(3.9 μm) was used previously by Pavolonis and Heidinger (2004) to infer cloud phase at night. Figure 2 shows the maximum amount of skill both the ems(3.9 μm) and BTD(3.9-11 μm) have when detecting fog/low clouds alone. SEVIRI data were used in this analysis. As Figure 2 shows, the ems(3.9 μm) parameter results in a greater possible skill score (blue line) when an optimal threshold of 0.7 is used compared to the optimal threshold of -7.0 for the BTD(3.9-11 μm). For the ems(3.9 μm) parameter, a maximum skill score of 0.69 can be obtained compared to 0.59 when using the BTD(3.9-11 μm), further backing up the reasoning behind using the ems(3.9 μm) parameter over the BTD(3.9-11 μm) for fog/low cloud detection.

$$ems(3.9\mu m) = \frac{R_{obs}(3.9\mu m)}{B(3.9\mu m, BT(11\mu m))} \qquad \text{Eq. 1}$$

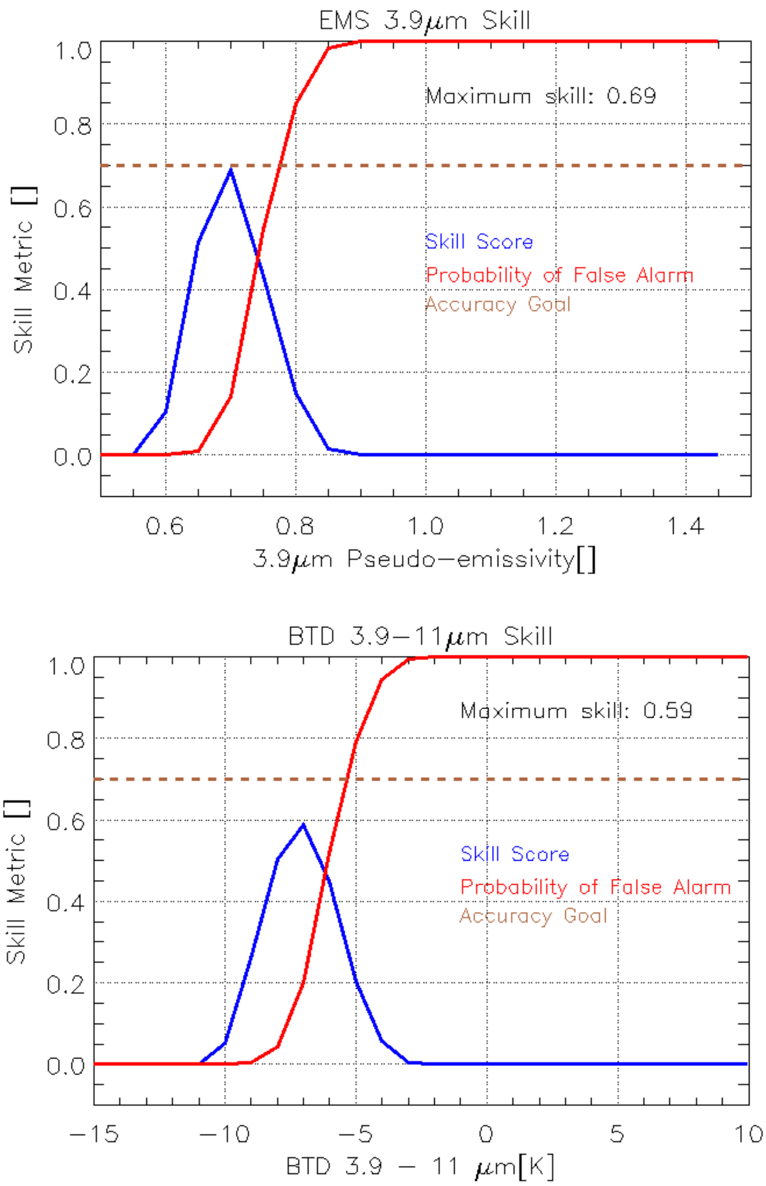


Figure 2 - The calculated skill score (blue line) obtained using the ems(3.9 μm) parameter (top) or BTD(3.9-11 μm) (bottom) when attempting to detect fog/low cloud alone. SEVIRI data were used in this analysis. The peak of the blue line represents the optimal threshold (x-axis) for each parameter, which resulted in the highest skill score. The red line represents the false alarm rate obtained using any given threshold. The dotted line represents the accuracy goal of the GOES-R fog/low cloud detection algorithm.

1.11.2.1.2 *Radiometric Surface Temperature Bias*

In window channels, infrared radiances can be used to retrieve the surface temperature (T_{sfc}) if the surface emissivity (ε_{sfc}), total gaseous atmospheric transmittance (t_{atm}), and the top of atmosphere upwelling clear sky atmospheric radiance (R_{atm}) are all known. The radiometric surface temperature bias can then be calculated as the difference between the modeled surface temperature (skin temperature) and the retrieved surface temperature. Equations 2 and 3 show the steps required to calculate the 11 μm surface temperature.

$$R_{sfc}(11\mu m) = \frac{R_{obs}(11\mu m) - R_{atm}(11\mu m)}{t_{atm}(11\mu m)} \qquad \text{Eq. 2}$$

$$T_{sfc}(11\mu m) = \frac{B^{-1}(11\mu m, R_{sfc}(11\mu m))}{\varepsilon_{sfc}(11\mu m)} \qquad \text{Eq. 3}$$

where B^{-1}( ) is the inverse Plank function. The radiometric surface temperature bias is then calculated using Equation 4 by taking the difference between the radiometric surface temperature and the surface temperature from an NWP model.

$$T_{bias} = T_{sfc}(11\mu m) - T_{sfc}(NWP) \qquad \text{Eq. 4}$$

In an ideal scenario, where the surface emissivity (ε_{sfc}), total gaseous atmospheric transmittance (t_{atm}), and the top of atmosphere upwelling clear sky atmospheric radiance (R_{atm}) are all known exactly and the modeled surface temperature was also correct, the radiometric surface temperature bias where clouds are not present should be very close to 0 K. However, errors in the modeled surface temperature and the variables needed to calculate the radiometric surface temperature result in biases in the radiometric surface temperature difference calculation. Heidinger and Pavolonis (2009) used Advanced Very High Resolution Radiometer (AVHRR) data to determine the bias between the retrieved 11 μm surface temperature and modeled surface temperature where clouds were not present. That study found that the biases were the greatest over land around the local solar noon (when the Sun is directly overhead), while over water the biases stayed small. This is most likely due to solar heating of the land that may not be fully accounted for in the modeled surface temperature. The same analysis performed by Heidinger and Pavolonis (2009) was replicated using GOES-12 data for a 24-hour period on July 1, 2009 and is shown in Figure 3. The biases over land again were found to be greatest (~ 6±6 K) around the local solar noon while the bias at night and over water remained relatively small (~ -2±2 K). Although currently not being taken into account, these biases may be helpful to diurnally correct the radiometric surface temperature bias for use in the fog/low cloud algorithm.

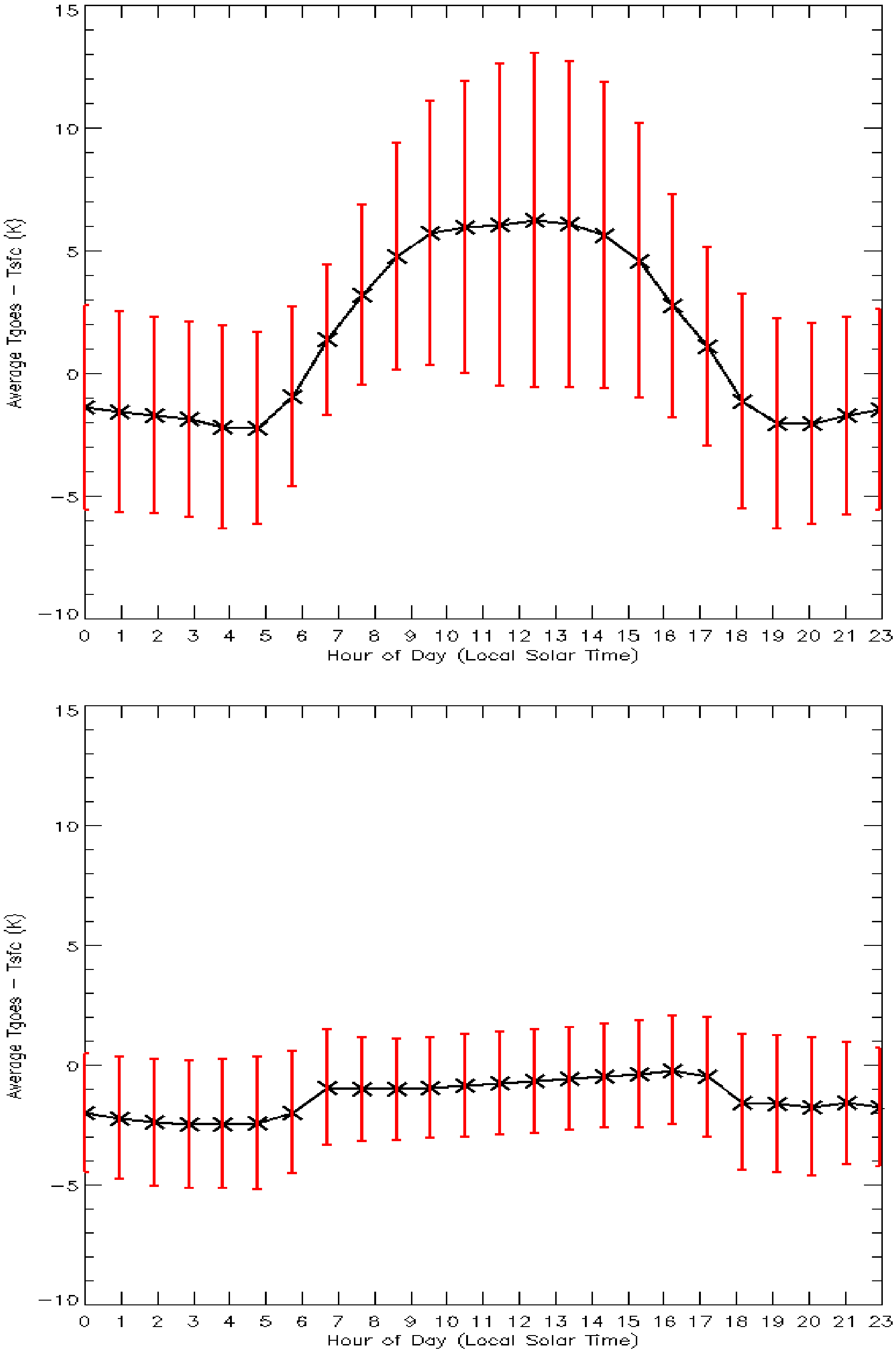
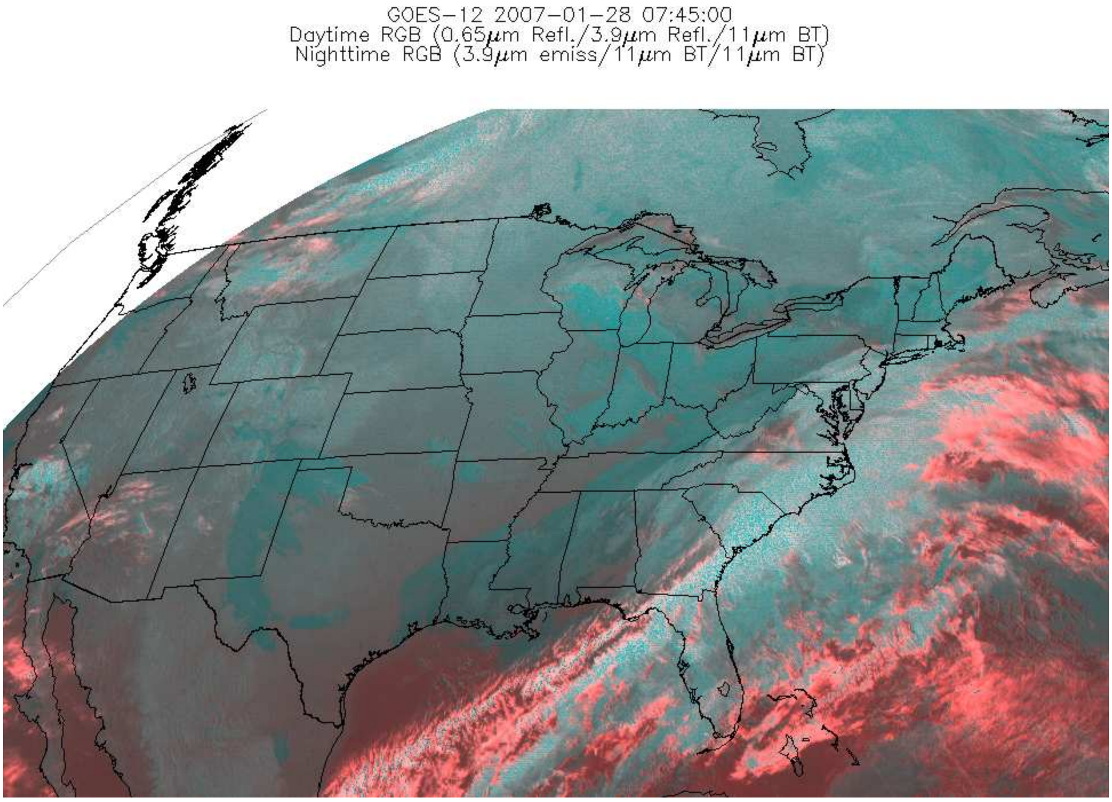


Figure 3 – 24-hour analysis of the clear sky, full disk radiometric surface temperature bias (GOES-12 11 µm retrieved temperature – modeled surface temperature) over land (top) and water (bottom) at each pixel's local solar time. The black lines and symbols represent the average temperature difference while the red error bars represent the standard deviation.

The radiometric surface temperature bias is useful for distinguishing fog/low clouds from liquid water clouds with high bases that do not meet the fog/low cloud criteria. Fog and low clouds are close to the surface and therefore should have a radiometric surface temperature that is similar to the actual surface temperature. Higher-based and non-stratus clouds tend to be colder than the surface and usually have a radiometric surface temperature that is significantly colder than the surface temperature. Ellrod (2000) used a similar metric to help identify clouds that cause Instrument Flight Rule (IFR) conditions. Figure 4 shows and RGB image and the corresponding radiometric surface temperature bias for a GOES-12 scene over the continental United States (CONUS).



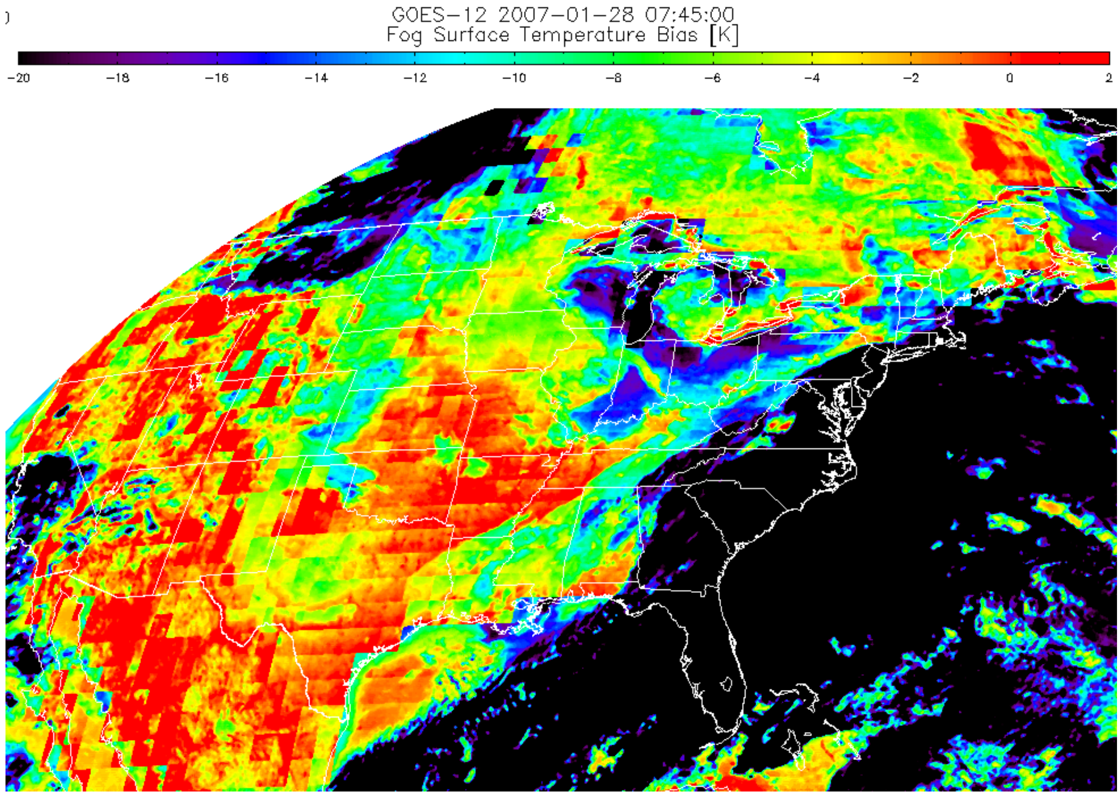


Figure 4 – GOES-12 RGB image (top) and corresponding radiometric surface temperature bias (bottom) calculated over CONUS from January 28, 2007 at 7:45 UTC.

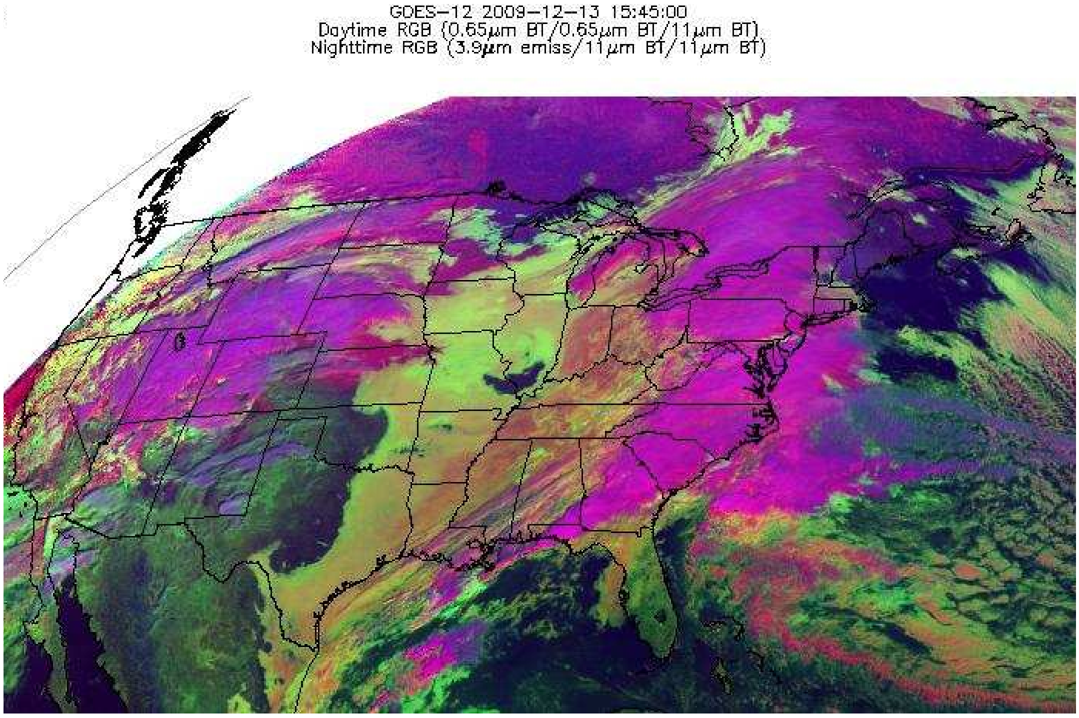
In Figure 4, the areas colored in yellow to red indicate where there is clear sky or very low clouds. The blue to black areas show where higher, colder clouds are likely present.

1.11.2.1.3 *Spatial Uniformity*

Fog and low cloud usually form in relatively stable environments with little vertical motion. For this reason fog/low cloud tend to be spatially uniform in both temperature and reflectivity. The spatial uniformity metric is used throughout the ABI fog detection algorithm for both the 11 μm brightness temperature (BT) and 0.65 μm reflectance. The spatial uniformity is determined by calculating the standard deviation of a 3x3 pixel array centered on any given pixel. The standard deviation of the 9 pixels is stored as the spatial uniformity value for the central pixel. This calculation is performed for each valid pixel in a given scene.

1.11.2.1.4 *Cloud Mask and Phase*

The ABI cloud mask and cloud phase products are used by the fog detection algorithm. During the day, the cloud mask is used to eliminate all pixels flagged by the cloud mask as being cloud free. The cloud phase is used during the day and at night to eliminate pixels flagged by the cloud phase algorithm as being completely composed of ice (both and day and night). The cloud mask output is not used at night, as it was not specifically designed to detect low clouds at night. Using the cloud mask and phase output increases the computational efficiency of the cloud object component (see Section 1.11.2.3) of the fog detection algorithm and reduces the potential for false alarms. The fog algorithm currently does not specifically look to identify ice fog due to its rare occurrence (temperature below -30°F with a sufficient amount of water vapor). Figure 5 below shows a GOES-12 false color image and the corresponding cloud phase/type product.



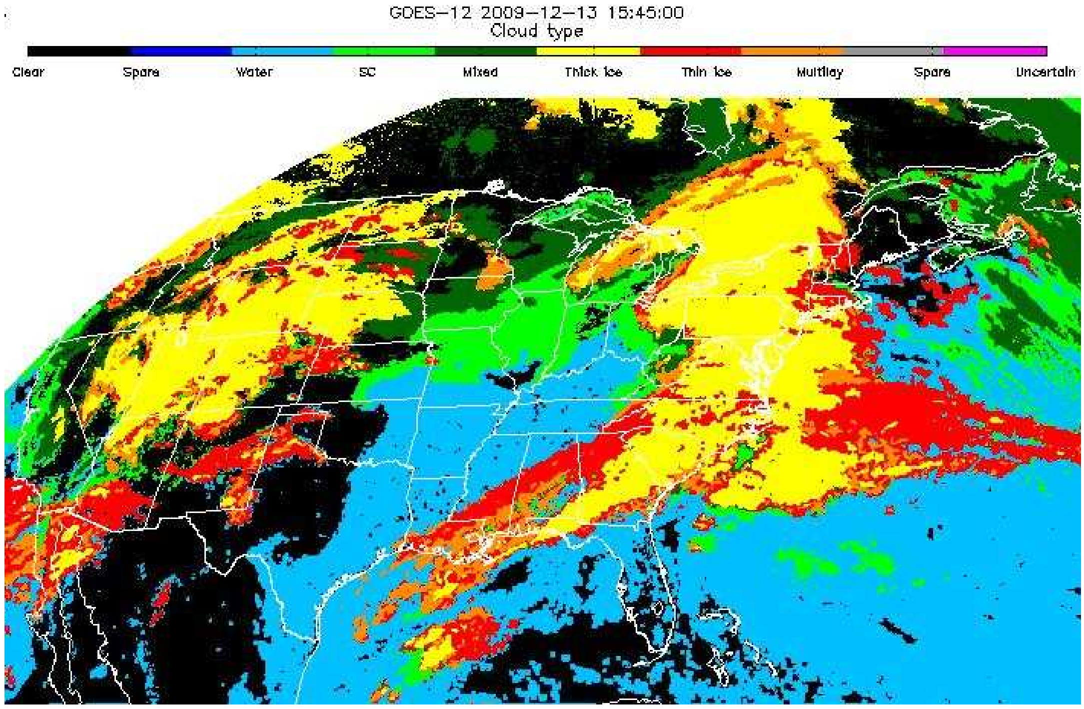


Figure 5 - GOES-12 false color image (top) using the 0.65, 3.9 and 11 µm channels with accompanying cloud type product (bottom) from the ABI cloud type algorithm. The cloud type category 'SC' refers to super cooled-type clouds.

1.11.2.2 Assessing Fog Probability

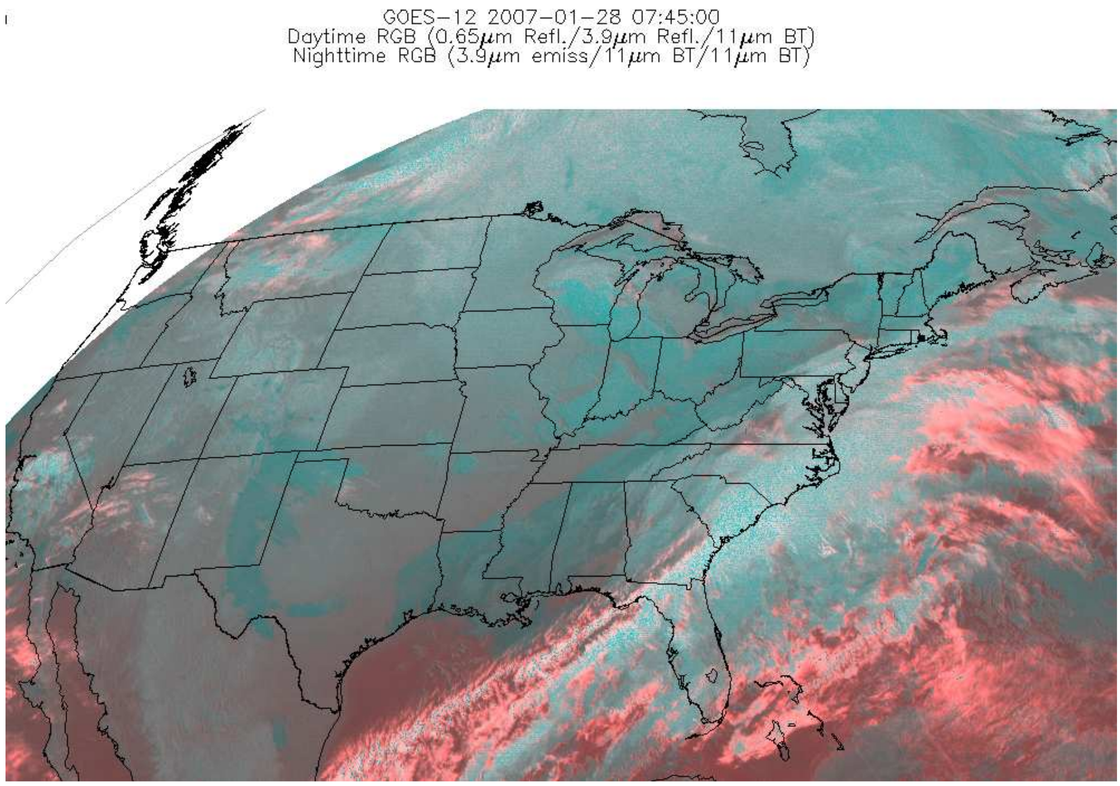
The ABI fog/low cloud mask uses a probabilistic approach to detect fog and low stratus clouds. Therefore, after the cloud mask and type check is performed the next step is to estimate the probability that each pixel contains fog/low cloud. This is done using pre-determined look-up tables (LUT's). These LUT's are described in detail in the following sections.

1.11.2.2.1 *Nighttime Probability*

The nighttime LUT's used to estimate the probability that fog/low cloud is present are dependent on the following three parameters:

1. 3.9 µm pseudo-emissivity (ems(3.9µm))
2. Radiometric surface temperature bias (T_{bias})
3. 3.9 µm surface emissivity

The 3.9 μm pseudo-emissivity, which was discussed in Section 1.11.2.1.1, is a key parameter in the nighttime fog probability LUT. Low water clouds with small particles have a smaller cloud emissivity at 3.9 μm than 11 μm. In addition, fog tends to be located in vertical layers that have a very small lapse rate, which limits the impacts of cloud transmission on the observed radiance. Thus, the 11 μm brightness temperature will be larger than the 3.9 μm brightness simply because the 11 μm cloud emissivity is greater than the 3.9 μm cloud emissivity and the impact of cloud transmission is minimal due to the small lapse rate. As such, the ems(3.9μm) is most often << 1.0 when fog is present, and clouds that have a ems(3.9μm) << 1.0 will have a higher fog probability. Figure 6 shows an RGB image and the ems(3.9μm) for a GOES-12 scene over CONUS. Values of ems(3.9μm) < 0.9 often correspond to areas of fog.



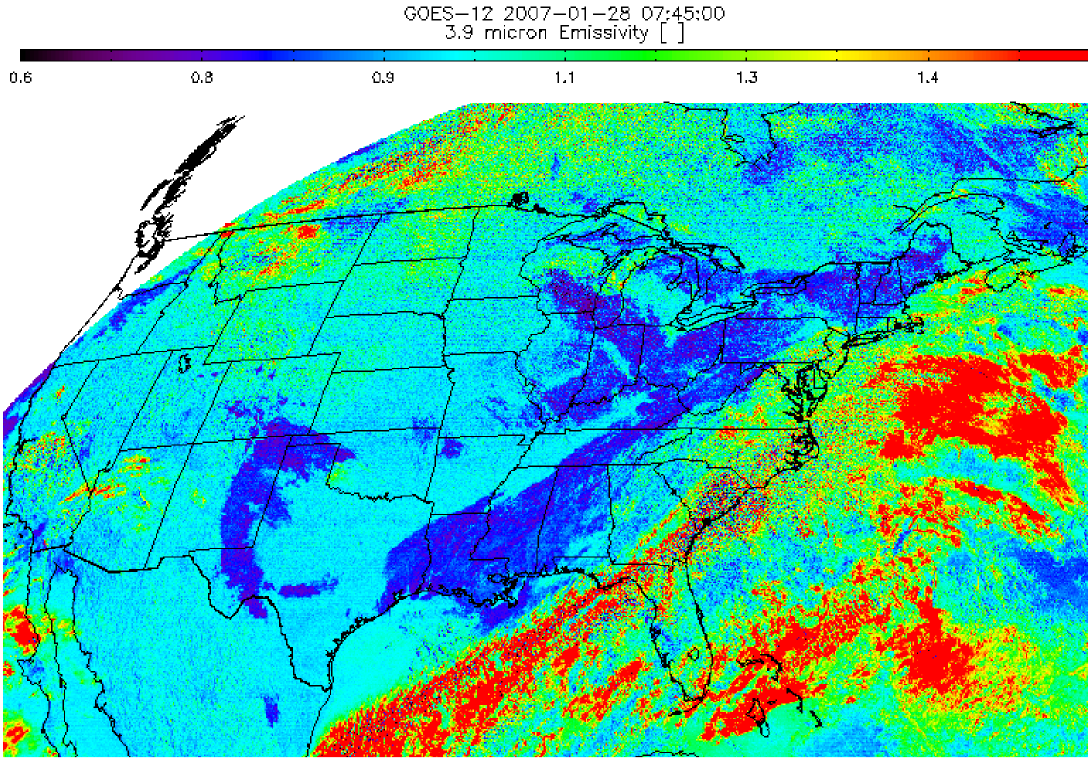


Figure 6 – GOES-12 RGB image (top) and 3.9 µm pseudo-emissivity (bottom) over CONUS on January 28, 2007 at 7:45 UTC.

The radiometric surface temperature bias (see Section 1.11.2.1.2) is also a predictor in the fog probability LUT. As described earlier, fog and low stratus clouds generally form in an isothermal or near-isothermal atmosphere with little vertical motion and vertical extent. Since fog/low stratus clouds are close to the ground the temperature of the cloud should be similar to the surface temperature. Due to the atmospheric lapse rate, clouds cool with respect to height, therefore cloud decks higher above the surface should be colder and thus have a larger radiometric surface temperature bias.

When the 3.9 µm surface emissivity is significantly less than the 11 µm surface emissivity (such as over deserts), the clear sky ems(3.9µm) will have similar values as the ems(3.9µm) of foggy pixels. Thus, the 3.9 µm surface emissivity is included as a parameter in the nighttime fog probability LUT. Figure 7 shows the 3.9 µm surface emissivity over CONUS. Note the relatively low surface emissivity over the desert southwest in Figure 7. In order to reduce the number of false alarms over areas of low surface emissivity multiple 2-dimensional LUT's (using ems(3.9µm) and T_{bias} as the two predictors) were created separating surfaces with lower/higher surface emissivity. Separate LUT's were created for land surfaces with emissivities above/below 0.90 (see Figure 8).

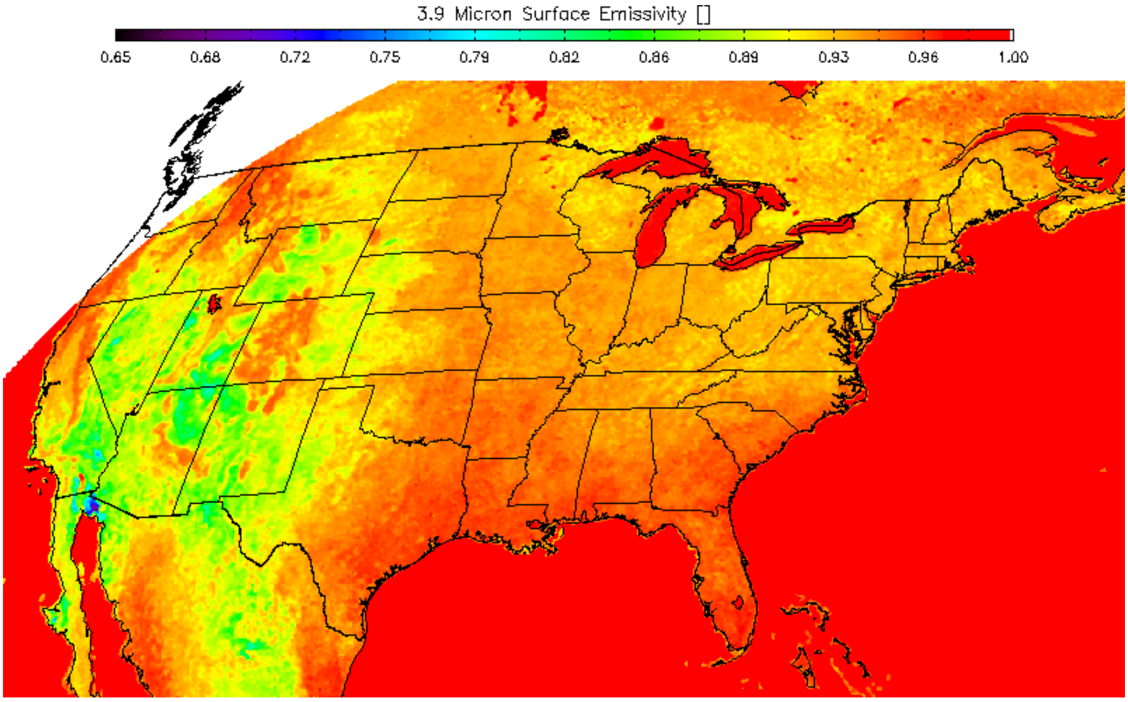
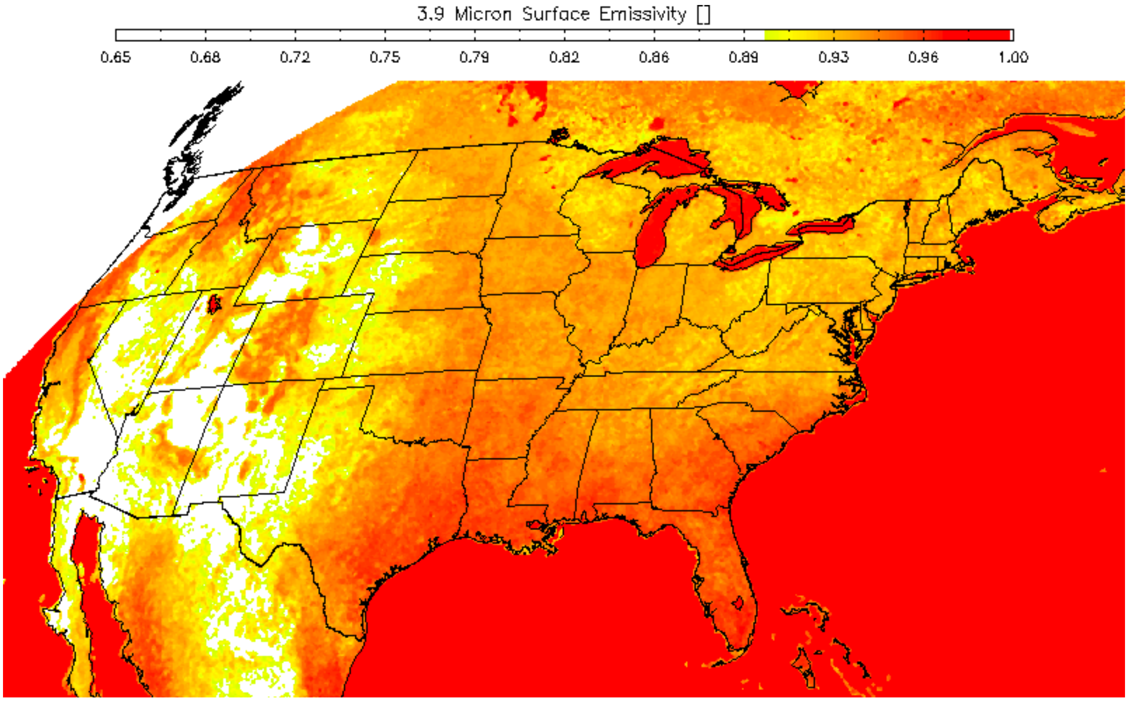


Figure 7 - 3.9 μm surface emissivity over CONUS.



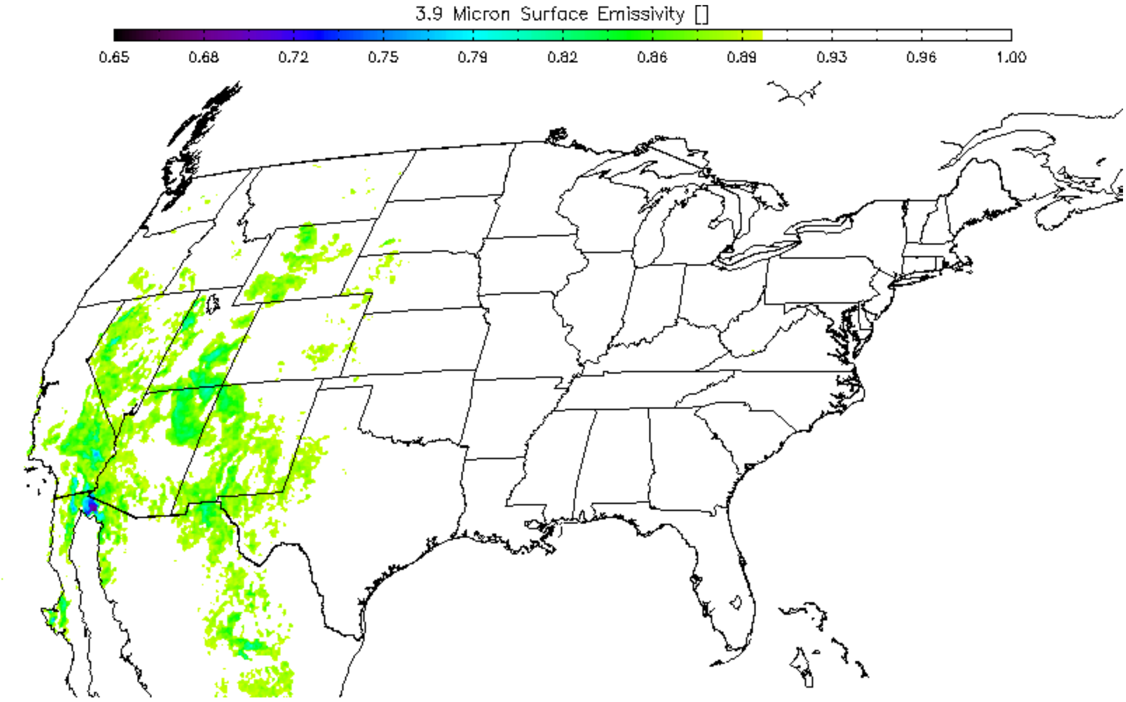


Figure 8 - 3.9 μm surface emissivity greater than or equal to 0.90 (top) and less than 0.90 (bottom).

1.11.2.2.1.1 Nighttime Fog Probability LUT's

Using the three parameters described above in section 1.11.2.2.1, LUT's were created to estimate the probability that fog/low stratus clouds are present given a pixel's spectral information. A month of GOES-12 data (September 2009) along with collocated surface observations (see section 2.1.2 for information about source and accuracy) were used to create the LUT's. Surface observations of cloud ceiling were used to identify pixels that had a ceiling of 1000 m or less to ensure that very few IFR conditions result in a low fog probability. As will be described in upcoming sections, cloud object statistics will be used to eliminate non-IFR producing clouds.

For nighttime fog/low cloud detection two separate LUT's were created for surfaces with 3.9 μm emissivities below/above 0.90. Each LUT is two-dimensional with respect to ems(3.9μm) and surface temperature bias. The surface temperature bias is separated into 20 bins ranging from -18 K to 0 K with a bin size of 1 K. The first bin contains all values that are less than -18 K and the last bin is for all values greater than 0 K. The 3.9 μm pseudo-emissivity is separated into 15 bins ranging from 0.80 to 1.06 with a bin size of 0.02. Again, the first bin contains all values less than 0.80 and the last bin contains all values greater than 1.06. This results in a 2x15x20 bin array LUT. All pixels with a collocated surface observation for the sample period were separated into their respective bin depending on their surface emissivity, pseudo-emissivity and surface temperature bias. A count of surface observations that indicated fog/low cloud or no fog/low cloud was recorded for each bin and used to calculate the probability that fog/low cloud is present given a pixel's 3.9 μm pseudo-emissivity and surface temperature bias information. The resulting LUT's are shown in Figure 9.

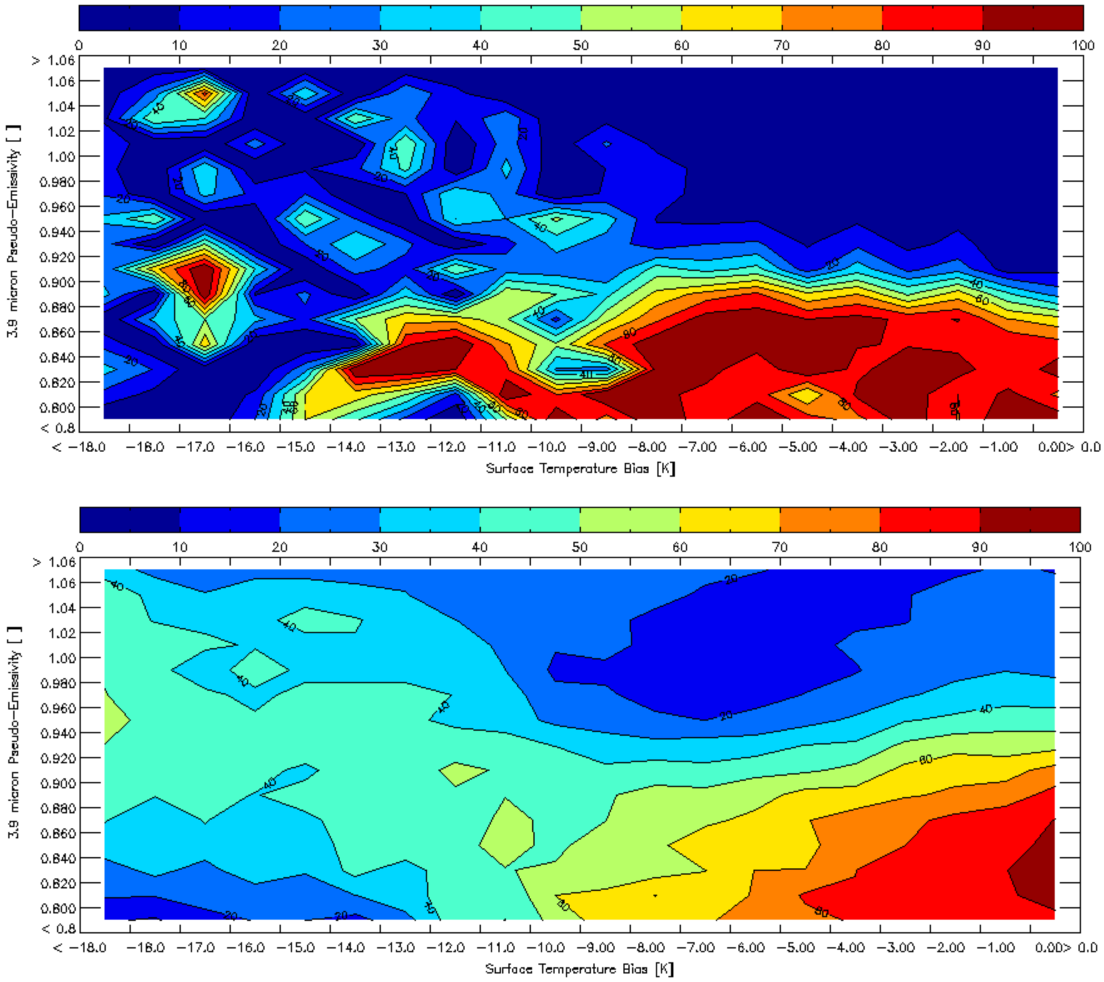


Figure 9 - Nighttime fog probability LUT's for surface emissivities less than 0.90 (top) and greater than or equal to 0.90 (bottom).

The probability that fog/low cloud is present for each GOES-12 pixel flagged as either clear sky or water, mixed or super cooled cloud by the ABI cloud phase/type algorithm is estimated by applying the LUT's. Figure 10 shows the result of applying the LUT probabilities to a GOES-12 scene over CONUS from December 13, 2009.

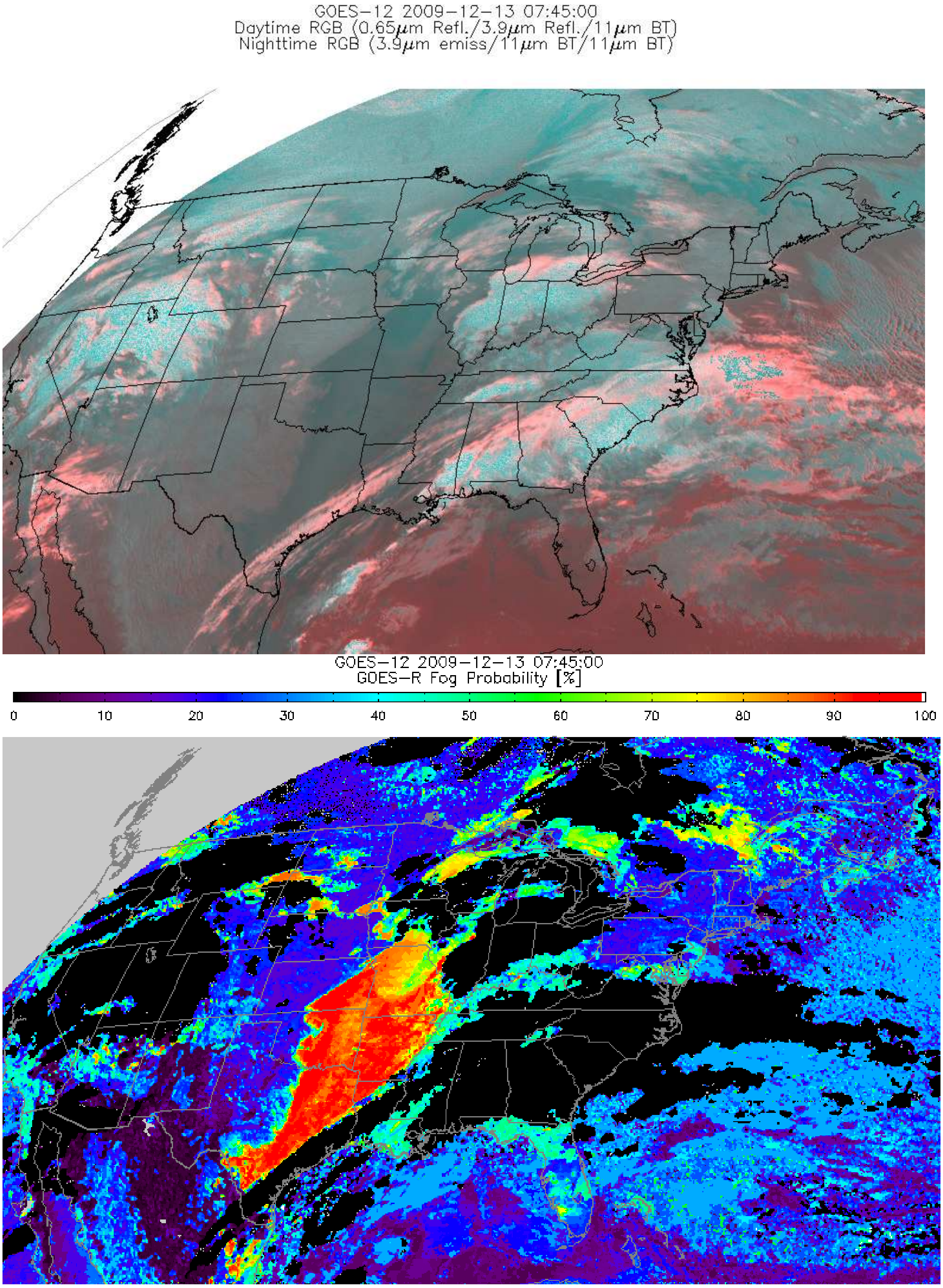


Figure 10 – RGB image (top) and fog/low cloud probability (bottom) from the nighttime LUT applied to a GOES-12 scene over CONUS from December 13, 2009

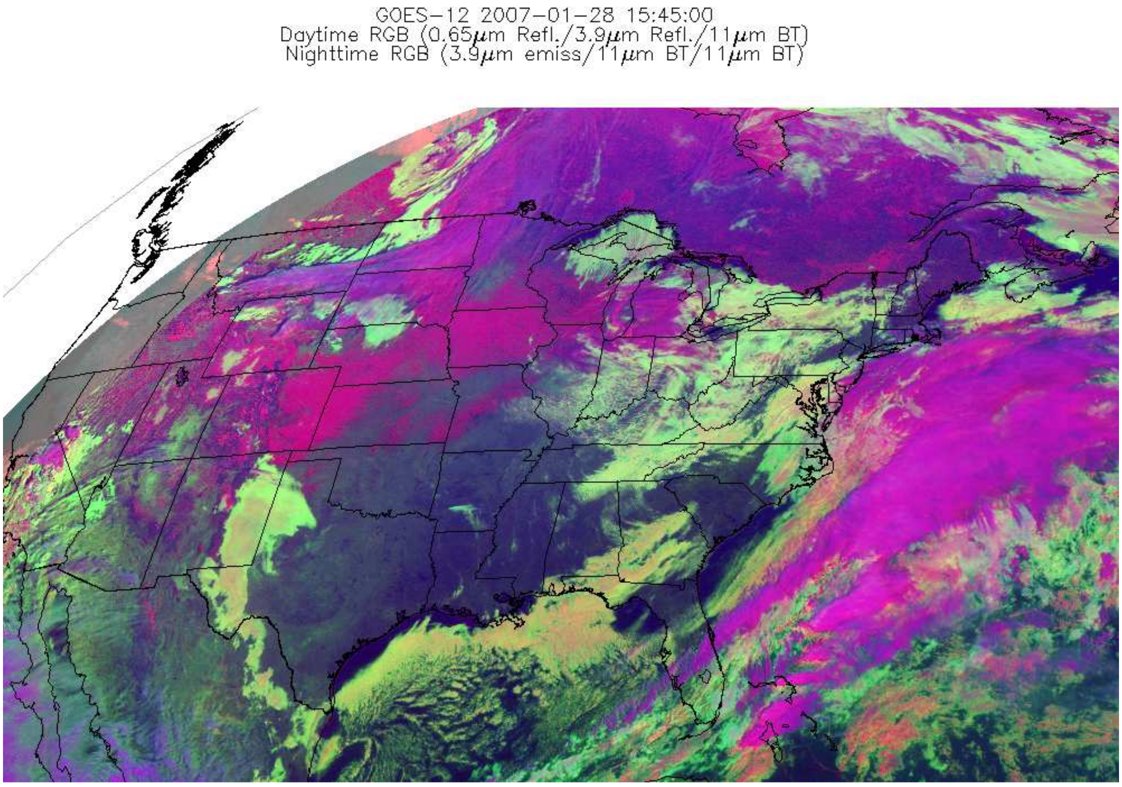
at 7:45 UTC. Black areas indicate pixels flagged as ice cloud by the cloud phase algorithm.

1.11.2.2.2 *Daytime Probability*

The daytime LUT used to estimate the probability that fog/low cloud is present is dependent on the following two parameters:

1. 11 μm BT spatial uniformity
2. Radiometric surface temperature bias

As previously discussed, fog/low stratus clouds tend to be spatially uniform in 11 μm brightness temperature (BT). This is because fog and low stratus clouds form in relatively stable environments with little vertical motion. The 3x3 (pixel array) 11 μm BT spatial uniformity calculation can be used to identify pixels that are located in a cloud that is spatially uniform in BT, and therefore have a higher probability of being a IFR producing low cloud. Figure 11 shows the 11 μm BT spatial uniformity for a GOES-12 scene over CONUS.



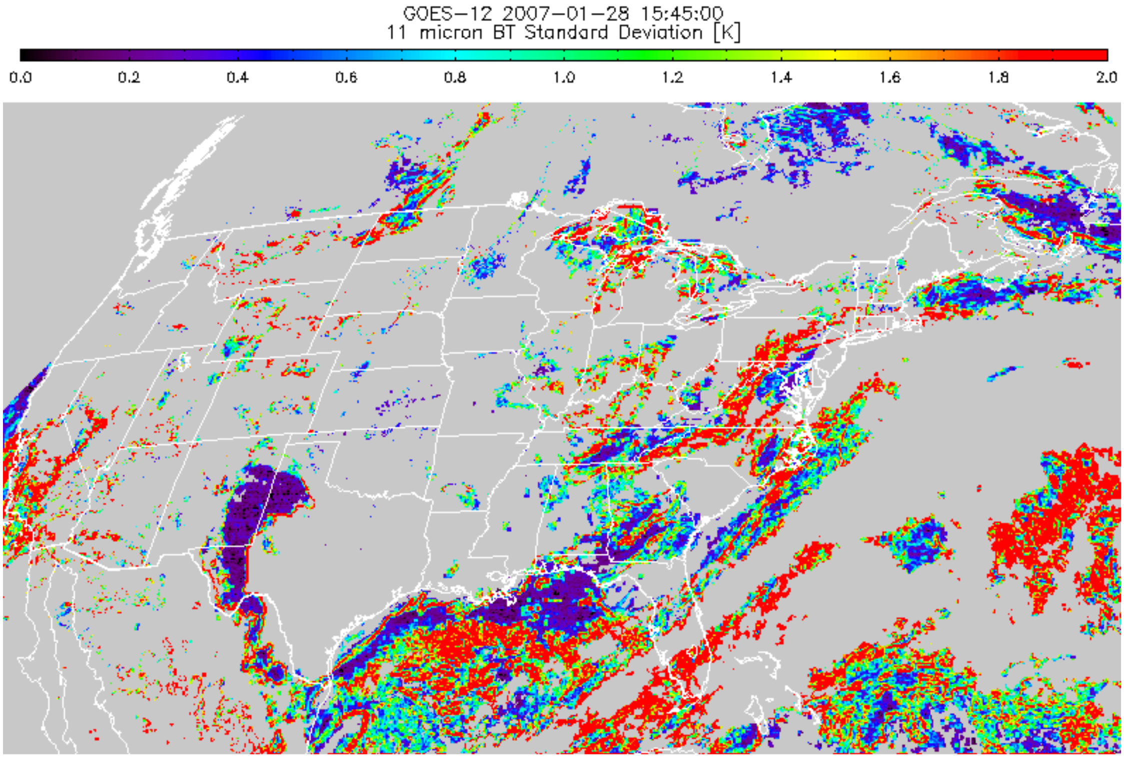


Figure 11 – RGB image (top) and the 3x3 pixel 11 µm BT spatial uniformity (bottom) calculated for a GOES-12 scene over CONUS on January 28, 2007 at 15:45 UTC. Gray areas are pixels flagged as either clear sky or ice cloud by the cloud phase algorithm.

The 11 µm BT spatial uniformity can be paired with the previously described radiometric surface bias to construct a 2-dimensional fog probability LUT.

1.11.2.2.2.1 Daytime Fog/Low Cloud Probability LUT

Using the two parameters described above, a LUT was created to estimate the probability that fog/low stratus clouds are present. A month of GOES-12 data (September 2009) along with collocated surface observations were used to create the LUT. Surface observations of cloud ceiling were used to identify pixels that contained fog/low cloud. As described in section 1.11.2.2.1.1 the conservative threshold of 1000 m for ceiling height from the surface observations was used to determine if a pixel contained fog/low cloud. Further tests should remove areas that are not fog/low cloud after cloud objects are created.

The surface temperature bias is separated into 22 bins ranging from -20 K to 0 K with a bin size of 1 K. The first bin contains all values that are less than -20 K and the last bin is for all values greater than 0 K. The 11 µm BT spatial uniformity is separated into 21 bins ranging from 0.10 to 1.00 with a bin size of 0.05. Again, the first bin contains all values less than 0.10 and the last bin contains all values greater than 1.0. This results in a 21x20 bin array LUT. All pixels with a collocated surface observation for the sample period were separated into their respective bin depending on their 11 μm BT spatial uniformity and surface temperature bias. A count of surface observations that indicated fog/low cloud or no fog/low cloud was recorded for each bin and used to calculate the probability that fog/low cloud is present given a pixel's 11 μm BT spatial uniformity and surface temperature bias information. The resulting LUT is shown in Figure 12.

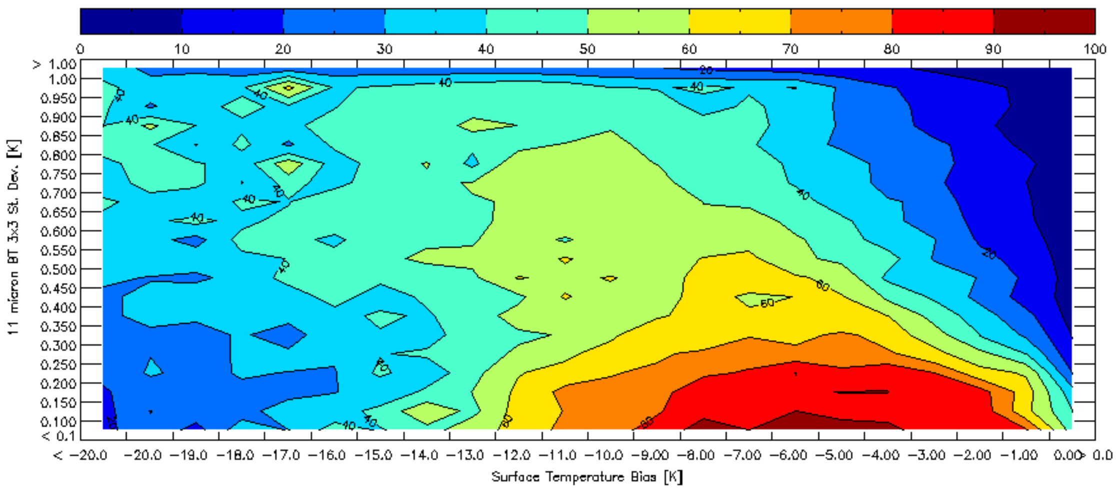


Figure 12 – Daytime fog probability look-up table.

The probability that fog/low cloud is present for each GOES-12 pixel flagged as either water, mixed or super cooled cloud by the ABI cloud type/phase algorithm is estimated by using the daytime LUT. Figure 13 shows the result of applying the LUT probabilities to a GOES-12 scene over CONUS from December 13, 2009.

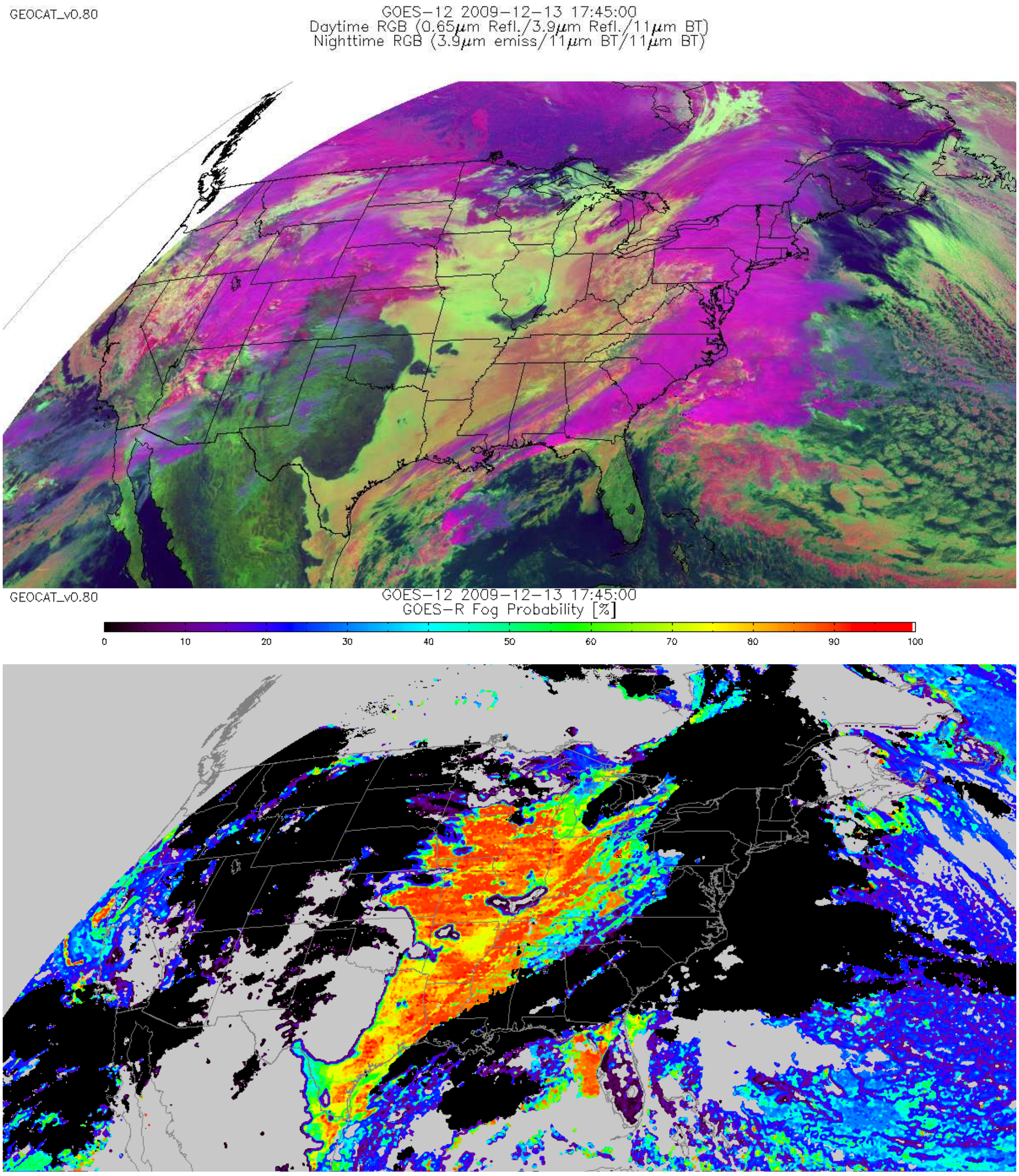


Figure 13 – RGB image (top) and fog/low cloud probability (bottom) from the daytime LUT applied to a GOES-12 scene over CONUS from December 13, 2009 at 17:45 UTC. Black areas indicate pixels flagged as ice cloud by the cloud phase algorithm. Gray areas indicate pixels flagged as being clear sky.

1.11.2.3 Constructing Cloud Objects

The F&PS requirements state that a fog/no fog mask is to be created. Thus, the fog probability must be screened. A cloud object based methodology is used to determine which clouds have the highest overall probability of producing IFR conditions. A cloud object is composed of spatially connected pixels that meet a certain set of criteria (object membership criteria). The methodology of Wielicki and Welch (1986) is used to construct cloud objects. The object membership criteria are described in the sections below.

1.11.2.3.1 *Fog Object Membership Criteria*

Before the cloud objects are formed a cloud object mask must be created to identify pixels that meet the object membership criteria. In the ABI fog detection algorithm, one set of cloud objects is created at night, and two sets of cloud objects are created during the day. At night, the object membership criteria are based on the fog probability. During the day, one set of cloud objects is formed using fog probability (using the same criteria as at night) to determine object membership, and a second set of cloud objects is formed using the radiometric surface temperature bias to determine object membership. The methods ("fog probability" and "radiometric surface temperature bias") for defining cloud object membership are described in detail in the following sections.

1.11.2.3.2 *Fog Probability Cloud Objects*

The first step in determining which pixels are used to create the fog probability cloud objects is to determine the probability that fog/low cloud is present in each pixel. This is done using pre-determined LUT's described in detail in sections 1.11.2.2.1.1 and 1.11.2.2.2.1. Once the fog probability is estimated, a threshold is used to remove pixels that have a very low fog probability from the cloud object generation mask. For pixels to meet the object membership criteria, they must have an estimated fog probability of at least 40%. The 40% threshold was manually chosen such that the edges of fog would meet the object membership criteria. Figure 14 shows examples of day/night fog probability object masks after the 40% threshold is applied to the same scenes shown in Figure 10 and Figure 13.

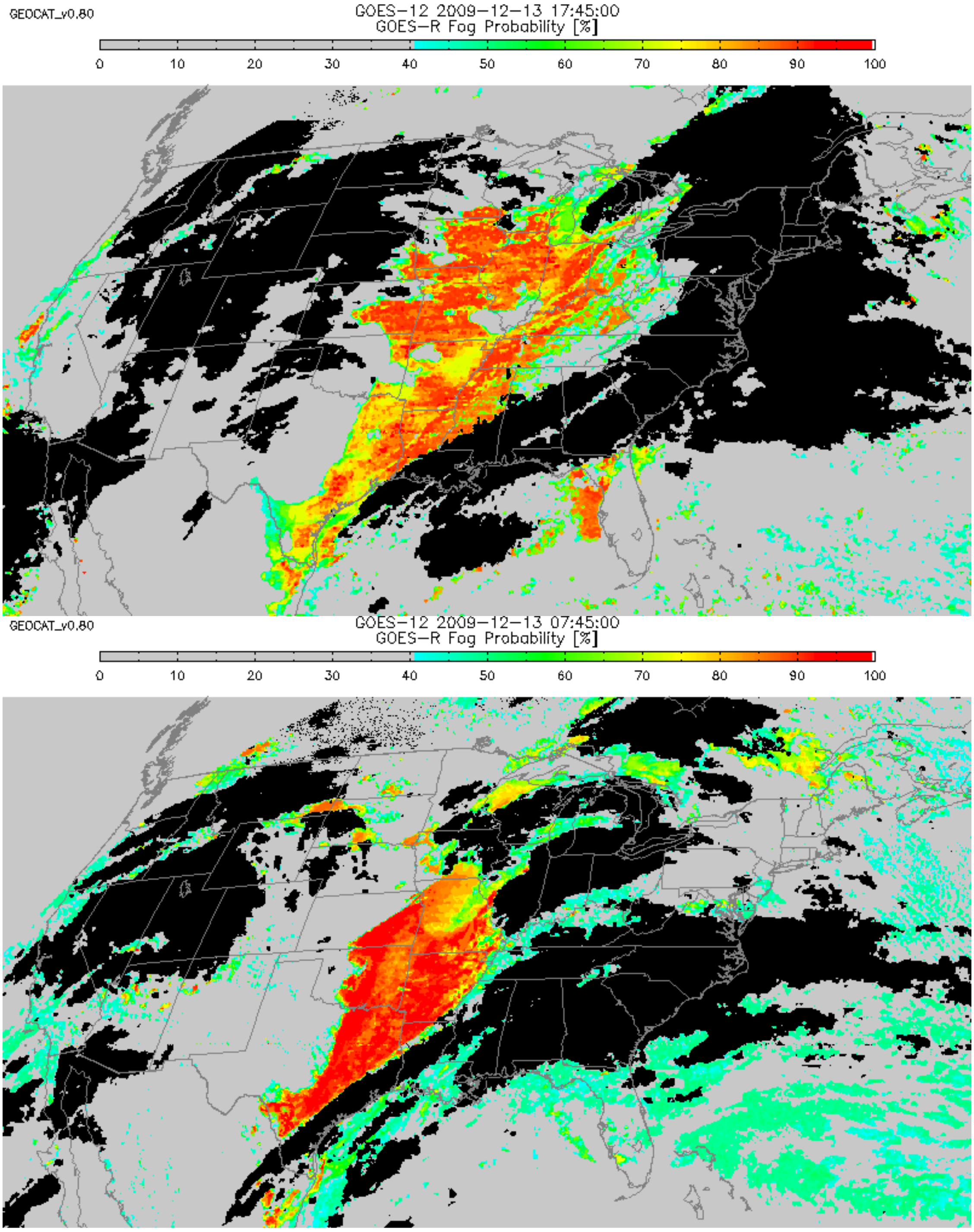


Figure 14 – Daytime (top) and nighttime (bottom) GOES-12 scenes showing fog probabilities greater than 40% that are used to make up the cloud object mask from December 13, 2009 at 7:45 UTC (top) and 17:45 UTC (bottom). Black areas are pixels flagged as ice cloud by the cloud phase algorithm and gray pixels are those

that have a probability less than 40%, both of which are not used to create cloud objects. These are the same scenes shown in Figure 10 and Figure 13.

The pixels remaining after the 40% threshold is applied are allowed to belong to cloud objects. The cloud object code uses the cloud object membership mask to create the cloud objects as described in Section 1.11.2.3.

Obviously not all pixels that are estimated to have a fog probability greater than 40% actually do contain fog/low cloud, but instead may be liquid water clouds with higher bases that do not meet the instrument flight rules (IFR) requirements. For this reason, the cloud objects are further analyzed using statistics created from pixels that make up each individual object in order to remove those that are considered not to be composed of fog/low cloud. This analysis is described in detail in section 1.11.2.3.4 below.

1.11.2.3.3 *Radiometric Surface Temperature Bias Cloud Objects*

Using the 11 μm BT spatial uniformity as a predictor in the daytime fog probability LUT works well for larger areas of fog, but often causes very small-scale fog events, such as river valley fog, and fog edges to have a low probability (lower than the 40% threshold used in constructing the fog probability objects). This is because cloud edges are not spatially uniform. In order to detect small-scale areas of fog/low cloud, a second set of cloud objects is created during the day. The object membership criteria of this second set of cloud objects (only created during the day) are based on the cloud mask, cloud phase, and radiometric surface temperature bias. The idea is to find areas of fog/low cloud that may be non-spatially uniform due to cloud edge effects. Any liquid water cloud, not located over a large body of water, with a radiometric surface temperature bias > -15 K meets the object membership criteria. Figure 15 shows the radiometric surface temperature bias for a small-scale valley fog event over the Northeast U.S. on September 17, 2007 at 13:15 UTC using GOES-12. A radiometric surface temperature bias threshold of -15.0 K was manually chosen after viewing several scenes to include all areas where fog/low cloud may be present. Figure 16 shows the surface temperature bias greater than -15.0 K at pixels classified as liquid water, super cooled liquid water, or mixed phase cloud by the ABI cloud type/phase algorithm for the same scene shown in Figure 15. The pixels remaining after the cloud phase and radiometric surface temperature bias threshold are applied (left image from Figure 16) make up the cloud object mask. The cloud object code uses this mask to create the cloud objects for each scene as described in Section 1.11.2.3.

Just as the fog probability object mask may contain pixels that do not actually contain fog/low cloud, not all pixels that make up the surface temperature bias objects are guaranteed to contain fog/low cloud. For this reason the objects must be further analyzed using their object-based statistics (see section 1.11.2.3.5) in order to remove objects that do not meet the fog/low cloud criteria.

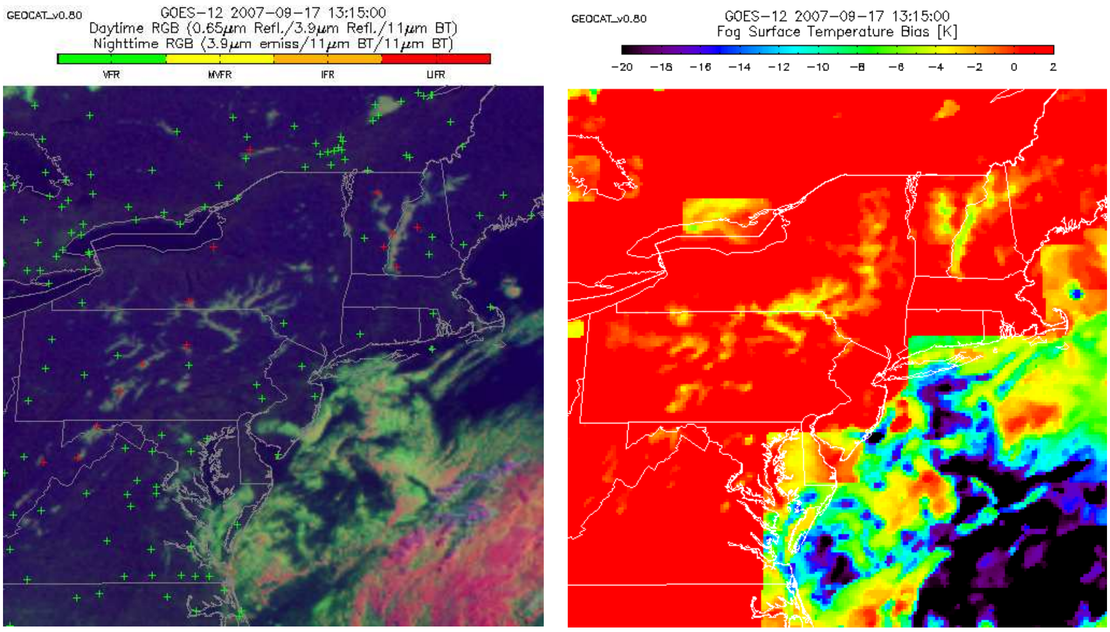


Figure 15 - False color RGB image (left) and surface temperature bias (right) of a valley fog scene over the Northeast U.S. from GOES-12 on September 17, 2007 at 13:15 UTC. The crosses on the false color RGB image indicate surface observations. Red crosses indicate ceilings that meet IFR ceiling criteria (fog/low cloud), green crosses indicate ceilings that do not meet IFR criteria (not fog/low cloud).

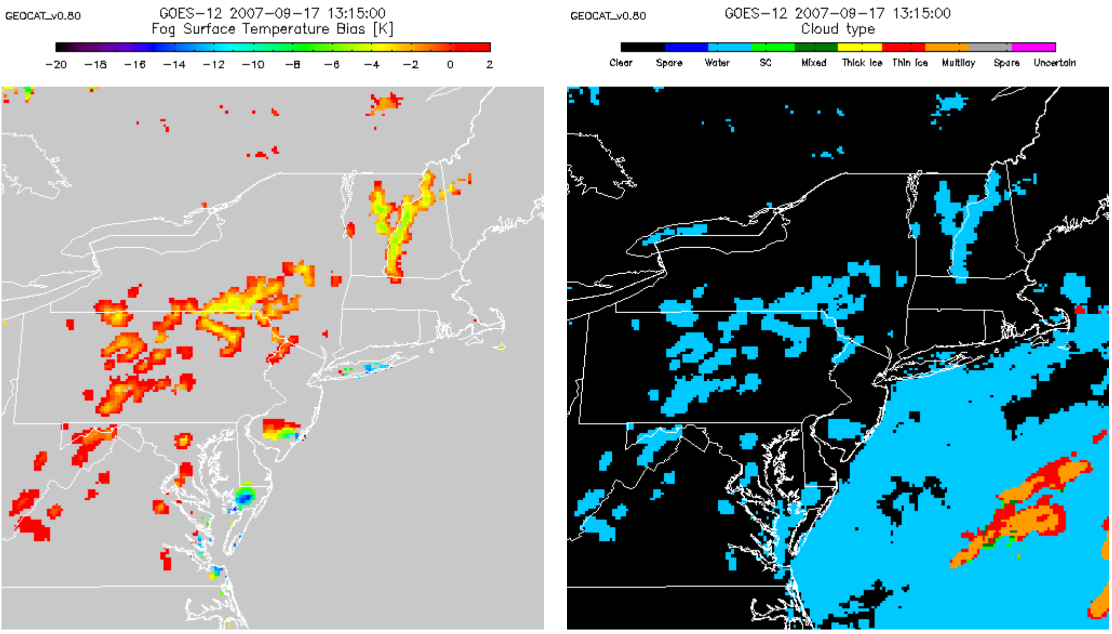


Figure 16 - The surface temperature bias over land (left) when greater than -15.0 K and water, mixed or super cooled clouds are flagged by the cloud type algorithm (right) (gray indicates areas where these conditions are not met) for the same GOES-12 valley fog scene as Figure 15 on September 17, 2007 at 13:15 UTC.

1.11.2.3.4 *Fog Object Statistics – Fog Probability Objects*

Cloud object statistics are computed for each cloud object. Recall that cloud objects are composed of a variable number of pixels. The cloud object statistics are calculated and stored as the cloud objects are created. As described in Section 1.11.2.3.1, the masks used to create the cloud objects serves as a first guess fog mask. Inevitably, non-fog pixels with spectral and textural properties similar to fog are included in this first guess fog mask. As such, the object statistics are used to filter the cloud objects to remove those that are most likely not fog from the final fog mask. Different statistics are used depending whether it is day or night. These statistics are described in the following sections.

1.11.2.3.4.1 **Daytime Fog Probability Object Statistics**

As previously discussed, there are several spectral and textural metrics that can be used to identify areas of fog/low cloud. During the day, low clouds are expected to be spatially uniform in both temperature and reflectance, and have a low radiometric surface temperature bias. The clouds should also have an elevated 0.65 μm and 3.9 μm reflectance when small liquid droplets are present, as is often the case with fog. Table 3 summarizes the daytime cloud object statistics used to filter the cloud objects, removing those that are unlikely to be fog.

Statistic Name	**Description**	**Fog/Low Cloud Requirement**
0.65 μm reflectance CDF	CDF made from the 0.65 μm reflectance values of every pixel in a given cloud object	50% of object pixels must have reflectance > 20%
0.65 μm spatial uniformity CDF	CDF made from the 3x3 pixel 0.65 μm reflectance spatial uniformity values of every pixel in a given cloud object	50% of object pixels must have a reflectance spatial uniformity < 5.0%
3.9/0.65 μm reflectance ratio object standard deviation	The standard deviation of the 3.9/0.65 μm reflectance ratios calculated using every pixel in a given object	Standard deviation using all object pixels < 0.5
3.9 μm reflectance CDF	CDF made from the 3.9 μm reflectance values of every pixel in a given cloud object	50% of object pixels must have reflectance > 5.0%
Surface temperature bias CDF	CDF made from the radiometric surface temperature bias values of every pixel in a given cloud object	50% of object pixels must have surface temperature bias > -10.0 K

Table 3 – Daytime cloud object statistics used to analyze the fog probability cloud objects. In this table, CDF is defined as Cumulative Distribution Function.

It should be noted, even though it has been repeatedly stated that an important characteristic of fog is being spatially uniform in temperature, that object statistics using the 11 μm BT are not used when analyzing the daytime cloud objects to avoid redundancy. This is because the fog probability used to create the cloud objects was based off of the 11 μm BT spatial uniformity, therefore further analyzing the cloud objects using 11 μm BT statistics would be redundant and unnecessary. The explanation and logic behind using the object statistics defined above to analyze the cloud objects is described in detail in Section 1.11.2.4. These statistical criteria are applied to each object. If all of the statistics meet the fog/low cloud requirement the object is kept. If even one of the statistics does not meet the requirement, all of the pixels in the cloud object are removed from the final fog/low cloud mask.

1.11.2.3.4.2 Nighttime Fog Probability Object Statistics

The nighttime cloud object criteria mask generally does a good job in identifying areas of fog and low cloud. The fog objects are still needed, however, to filter out some false alarms. For instance, some clouds, such as high-based stratus and liquid continental or marine stratocumulus, are often given a higher probability of containing fog/low cloud even though they do not meet the IFR ceiling requirement. A combination of the 11 μm BT spatial uniformity and radiometric surface temperature bias are used to filter out non-IFR producing stratocumulus clouds. Table 4 summarizes the nighttime cloud object statistics used to filter out false alarms.

Statistic	Description	Fog/Low Cloud Requirement
3x3 pixel 11 μm BT spatial uniformity CDF	CDF made from the 3x3 pixel 11 μm BT spatial uniformity values of every pixel in a given cloud object	50% of object pixels must have spatial uniformity < 0.5 K
Surface Temperature bias CDF	CDF made from the radiometric surface temperature bias values of every pixel in a given cloud object	50% of object pixels must have surface temperature bias > -15.0 K

Table 4 – Nighttime cloud object statistics used to analyze the fog probability cloud objects. In this table, CDF is defined as Cumulative Distribution Function.

The explanation and logic behind using the cloud object statistics shown in Table 4 is described in detail in Section 1.11.2.4. These statistical criteria are applied to each object. If both statistics meet the fog/low cloud requirement the object is kept. If either one of the statistics does not meet the requirement the entire cloud object is removed from the final fog/low cloud mask.

1.11.2.3.5 *Fog Object Statistics – Radiometric Surface Temperature Statistics*

Once the cloud objects are created using the cloud object mask based on the radiometric surface temperature bias, further analysis is required to remove objects that are created but do not contain fog/low cloud. To do this several cloud object statistics are calculated in order to filter out false alarms. This set of cloud objects is only created during the day so nighttime statistics are not necessary.

1.11.2.3.5.1 Daytime Radiometric Surface Temperature Bias Object Statistics

The statistics used to analyze the cloud objects created using the radiometric surface temperature bias are very similar to those used for the fog probability cloud objects. Since the 11 μm BT was not used to create this set of objects it is included in this set of object statistics. Radiometric surface temperature bias statistics are not used because the radiometric surface temperature is used to decide object membership. Table 5 summarizes the daytime cloud object statistics used to filter out false alarms.

Statistic	Description	Fog/Low Cloud Requirement
0.65 μm reflectance CDF	CDF made from the 0.65 μm reflectance values of every pixel in a given cloud object	75% of object pixels must have reflectance > 15%
3.9 μm reflectance CDF	CDF made from the 3.9 μm reflectance values of every pixel in a given cloud object	50% of object pixels must have reflectance > 5%
11 μm BT standard deviation	The standard deviation of the 11 μm BT calculated using every pixel in a given object	Standard deviation using all object pixels < 2.0 K
3.9/0.65 μm reflectance ratio standard deviation	The standard deviation of the 3.9/0.65 μm reflectance ratios calculated using every pixel in a given object	Standard deviation using all object pixels < 0.2

Table 5 – Daytime cloud object statistics used to analyze the radiometric surface temperature bias cloud objects. In this table, CDF is defined as Cumulative Distribution Function.

The explanation and logic behind using these object statistics to analyze the cloud objects are described in detail in Section 1.11.2.4. These statistical criteria are applied to each object. If all of the statistics meet the fog/low cloud requirement the object is kept. If even one of the statistics does not meet the requirement, all of the pixels in the cloud object are removed from the final fog/low cloud mask.

1.11.2.3.5.2 Nighttime Radiometric Surface Temperature Bias Object Statistics

Nighttime cloud objects are not created using radiometric surface temperature bias as they are during the day.

1.11.2.4 Object-Based Fog Decision Logic

1.11.2.4.1 Daytime Fog Decision Logic

For the ABI fog detection algorithm there are two sets of the cloud objects created during the day and, therefore, two sets of object statistics are needed to analyze the cloud objects. Sections 1.11.2.3.4.1 and 1.11.2.3.5.1 summarize the statistics used to remove objects that do not meet the fog/low cloud criteria. This section describes why each statistic was chosen and how the thresholds were determined.

1.11.2.4.1.1 Fog Decision Logic for Fog Probability Cloud Objects

This section describes the cloud object statistics used to analyze the daytime fog probability cloud objects.

1.11.2.4.1.1.1 0.65 μm Reflectance CDF

During the day, the availability of the visible channels allows the cloud mask to more accurately detect low clouds than at night. Assuming that all clouds are detected during the day, the cloud object masks are dependent on the cloud mask and cloud type/phase algorithms so cloud objects are created only where water clouds are detected. Because the cloud mask is heavily relied upon, pixels that are falsely identified as clouds can be passed on to the cloud objects. Although uncommon in large areas, objects created using pixels incorrectly detected as cloud can be identified using the 0.65 μm reflectance channel since the land/water background is usually much darker than cloud. Assuming that most pixels in the cloud object are relatively bright in the visible channel (shallow fog, although dim is still more reflective than land or water), cloud objects made from falsely detected cloud pixels can be removed from the final fog/low cloud mask.

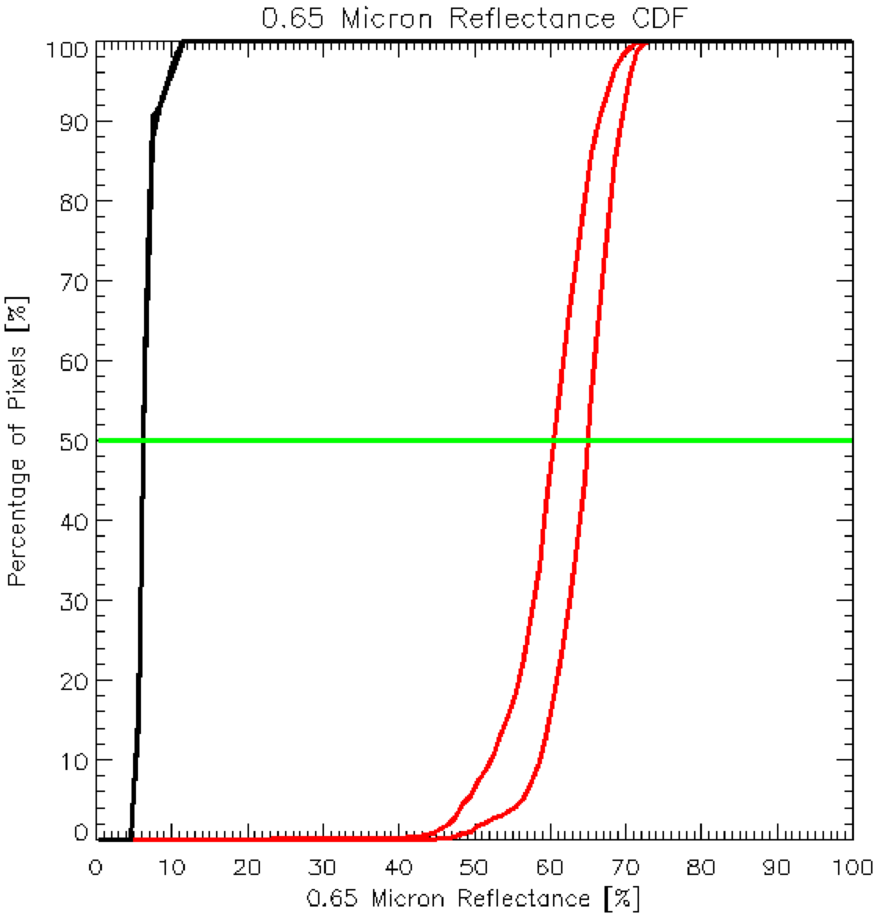


Figure 17 - CDF of the 0.65 µm reflectance for several manually chosen areas of fog/low cloud (red) and non-fog/low cloud (black). The green line represents where 50% of the pixels in the distribution have a 0.65 µm reflectance above the value it intersects the CDF.

Based on CDF's such as those from Figure 17, it was determined that as long as at least 50% of the pixels in any given cloud object have a 0.65 µm reflectance greater than 20% the cloud object is retained for further analysis. If that threshold is not met, the entire object is removed from the final fog/low cloud mask.

1.11.2.4.1.1.2 0.65 µm Reflectance Spatial Uniformity CDF

The low clouds being targeted by the fog/low cloud detection algorithm are stratiform in nature and therefore, due to the lack of vertical motion, should be spatially uniform in both temperature and reflectivity. The 11 µm BT spatial uniformity is already accounted for during the formation of the cloud objects so only the 0.65 µm spatial uniformity needs to be addressed with the fog probability object statistics. This parameter is used to separate cloud objects that are relatively uniform in temperature but not reflectance such as shallow continental cumulus or marine stratocumulus decks that do not pose a hazard to aviation. Looking at the distribution of the 3x3 pixel standard deviation of the 0.65 µm reflectance for each object allows objects with lower spatial uniformity to be identified and removed. Figure 18 contains the CDF's of several manually chosen areas containing fog/low cloud and non-fog/low cloud likely to be included in the daytime fog probability cloud objects. Surface observations of ceiling were used to determine if fog/low cloud was present.

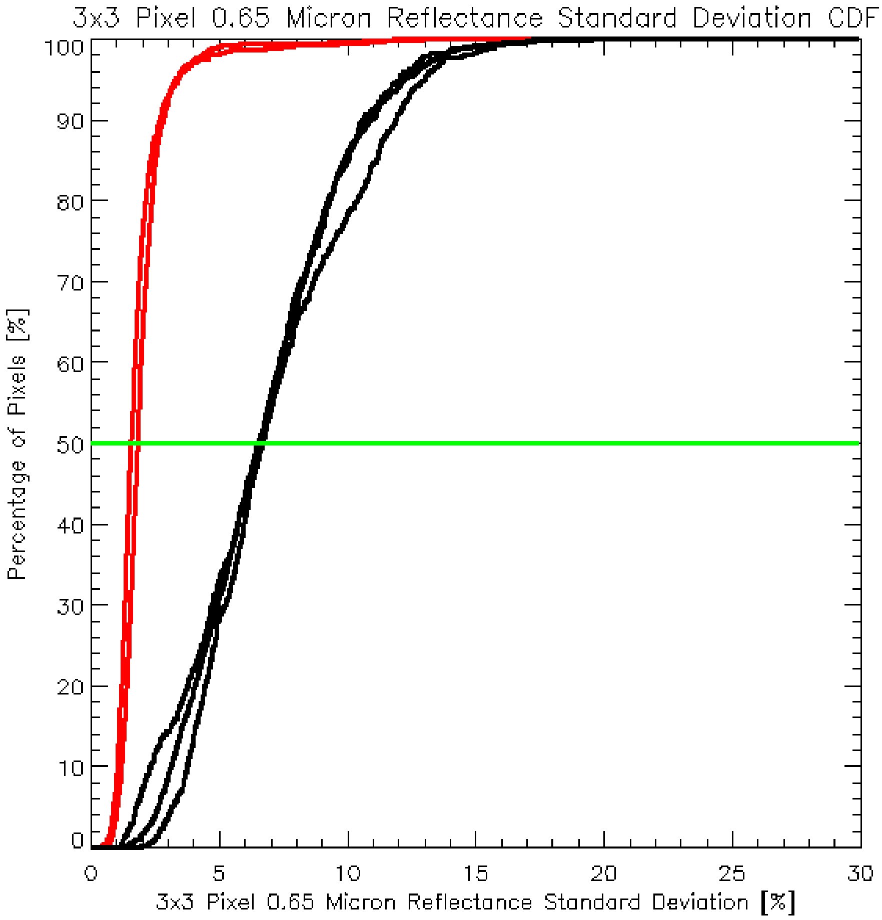


Figure 18 - CDF of the 3x3 pixel 0.65 µm reflectance spatial uniformity for several manually chosen areas of fog/low cloud (red) and non-fog/low cloud (black). The green line represents where 50% of the pixels in the distribution have a 0.65 µm reflectance spatial uniformity above the value it intersects the CDF.

Based on the CDF's, a threshold was chosen that distinguishes objects containing stratiform fog/low cloud from those that do not. The threshold chosen was 50% of the pixels in a given object must have a 3x3 pixel standard deviation of the 0.65 µm reflectance less than 5.0%. If this threshold is exceeded, the entire object is not considered to be fog/low stratus cloud and is removed from the final fog mask.

1.11.2.4.1.1.3 3.9 μm Reflectance CDF

Fog/low cloud often occurs during seasons when snow and ice are present. If these areas are falsely detected as cloud and are included in the cloud objects the visible and spatial uniformity statistics will not be effective at removing them since snow and ice fields are highly reflective in the 0.65 μm channel and spatially uniform in both temperature and reflectance. To ensure that the fog probability cloud objects are not composed of snow and/or ice the 3.9 μm visible reflectance channel is used. Snow and ice reflect poorly in the 3.9 μm window (usually < 2%). Therefore, using the distribution of the 3.9 μm reflectance, objects containing mostly clear sky pixels over snow/ice can be removed. Figure 19 contains the CDF's of several manually chosen areas containing fog/low cloud and non-fog/low cloud with snow/ice that might be included in the daytime fog probability cloud objects. Surface observations of ceiling were used to determine if fog/low cloud was present.

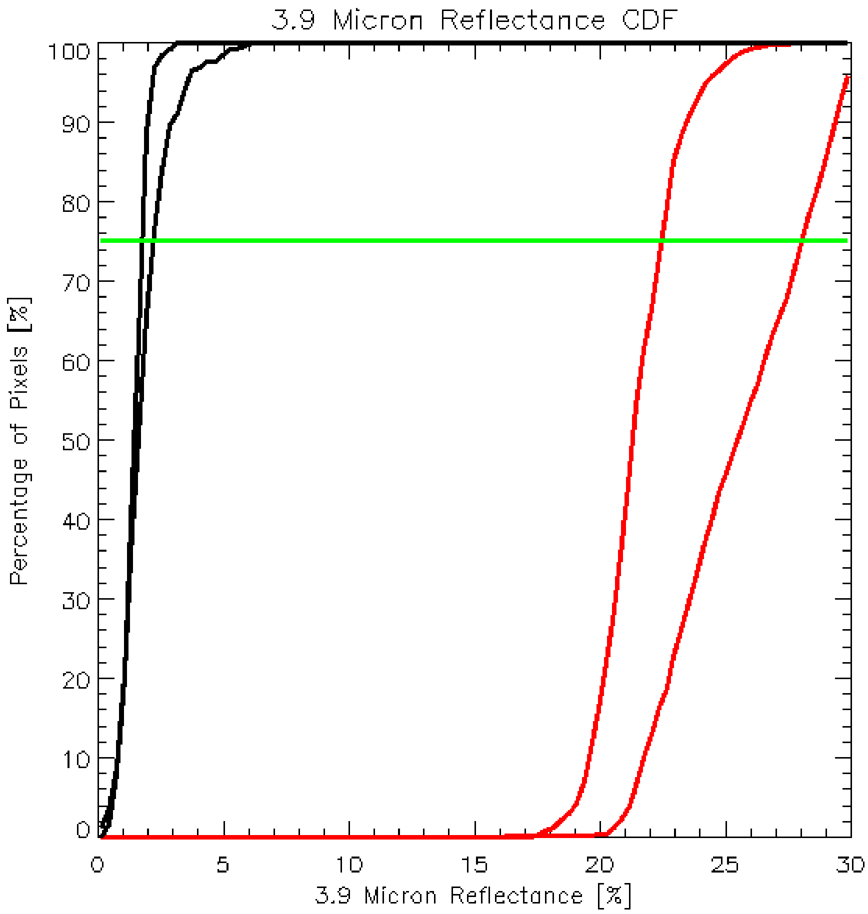


Figure 19 - CDF of the 3.9 μm reflectance for several manually chosen areas of fog/low cloud (red) and areas with unobstructed snow/ice (black). The green line represents where 50% of the pixels in the distribution have a 3.9 μm reflectance above the value it intersects the CDF.

As shown in Figure 19 the areas containing no fog/low cloud, but with snow/ice present have low values of reflectance at 3.9 μm. To remove these areas a threshold of at least 50% of the pixels in an object having a 3.9 μm reflectance of greater than 5% was chosen. If this threshold is not reached, the entire object is considered to not contain fog/low cloud and is removed from the final fog/low cloud mask.

1.11.2.4.1.1.4 Standard Deviation of the 3.9/0.65 μm Reflectance Ratio

The shortwave IR 3.9 μm channel is sensitive to both reflected and emitted IR radiation. During the day a large portion of the measured radiation comes from reflected energy. The amount of this reflected energy depends on the relative angle between the sun, cloud and satellite. In the terminator region, where solar zenith angles are relatively high (> 80°), when clouds with a large vertical extent are present the 3.9 μm channel can become erratic. This is because the reflected radiation does not only come from the top of the clouds but also the sides. Water droplets reflect more shortwave IR energy than ice crystals. When clouds composed of both water droplets (usually toward the bottom of the cloud) and ice crystals (at the top) are present at high solar angles the measured radiation may change depending on how much is reflected by different parts of the cloud. The 0.65 μm channel is highly reflective off both water droplets and ice crystals so changes are less dramatic. Using the standard deviation of the 3.9/0.65 μm reflectance ratios for an object allows cloud objects with wider distributions of the reflectance ratio to be identified and removed from the fog/low cloud mask, as they are unlikely to represent low, liquid stratiform cloud. After observing several scenes, a threshold of 0.5 was manually chosen to remove objects that are most likely not fog/low cloud but rather cloud edges most commonly seen at high solar zenith angles. Therefore, if any object has a 3.9/0.65 μm reflectance ratio standard deviation greater than 0.5, the entire object is removed from the final fog/low cloud mask.

1.11.2.4.1.1.5 Surface Temperature Bias

The surface temperature bias is already used to determine the probability that fog/low cloud is present at each pixel, but pixels with large biases may still return relatively high probabilities (> 40%) and be included in the fog probability cloud objects. In order to remove objects containing clouds that are unlikely to have cloud bases low enough to meet the IFR criteria, the distribution of the surface temperature bias is analyzed. Figure 20 shows the CDF's of several manually selected areas of both fog/low cloud and non-fog/low cloud that would likely be included in the fog probability cloud object mask. Surface observations of ceiling were used to determine if fog/low cloud was present.

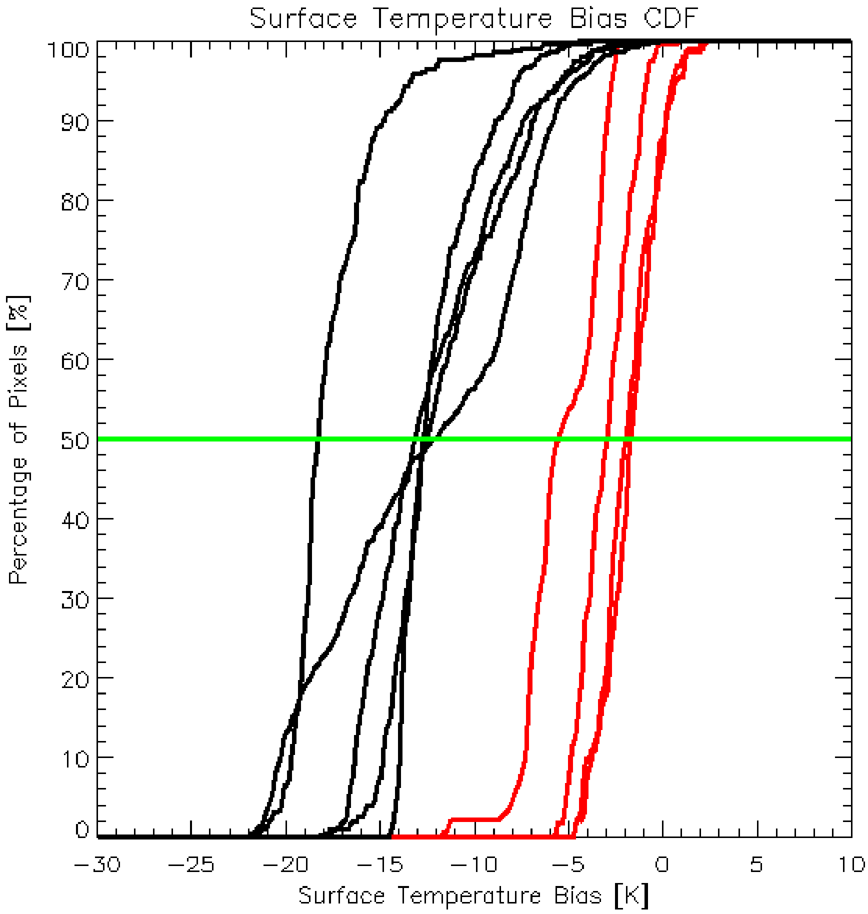


Figure 20 - CDF of the surface temperature bias for several manually chosen areas of daytime fog/low cloud (red) and non-fog/low cloud (black). The green line represents where 50% of the pixels in the distribution have a surface temperature bias above the value it intersects the CDF.

Based on the CDF's, a threshold was chosen that distinguishes objects containing fog/low cloud from those that do not. The threshold chosen was 50% of the pixels in a given object must have a surface temperature bias greater than -10.0 K. If this threshold is not reached the entire object is not considered to be fog/low cloud and is removed from the final fog mask.

1.11.2.4.1.2 Fog Decision Logic for Radiometric Surface Temperature Bias Cloud Objects

This section describes the object-based statistics used to analyze the daytime radiometric surface temperature bias cloud objects.

1.11.2.4.1.2.1 **0.65 μm Reflectance CDF**

The surface temperature bias cloud object mask is dependent on the cloud mask so any falsely detected cloud areas will likely make it into this set of cloud objects. One step used to remove these objects is to look at the distribution of the 0.65 μm reflectance for each object. Clouds should have a higher reflectance than the land background during the day, but may still appear relatively low in optically thin fog layers. The surface temperature bias cloud objects are generally smaller than the cloud objects created using the fog probability and commonly consist of shallow fog that is harder to detect. For this reason the threshold applied to the fog probability cloud objects as shown in section 1.11.2.4.1.1.1 is sometimes too high to capture the shallow fog signal. After manually analyzing the distribution of the 0.65 μm reflectance for objects from several scenes it was determined that if 75% of the pixels in a given object had a reflectance greater than 15% the object could be considered to contain fog/low cloud. If this threshold was not met the entire object was removed from the final fog mask.

1.11.2.4.1.2.2 3.9 μm Reflectance CDF

The distribution of the 3.9 μm reflectance was used ensure that cloud objects are not created from pixels falsely detected as cloud by the cloud mask, but instead consist of snow and/or ice. As previously mentioned snow and ice reflect poorly in the 3.9 μm window, which can be used to filter out objects that do not contain fog or low cloud. This test ensures that the spectral signal given off by snow/ice is not mistaken for fog/low cloud so the same threshold used for the daytime fog probability objects is used here (see section 1.11.2.4.1.1.3).

1.11.2.4.1.2.3 Standard Deviation of the 11 μm BT

The method for estimating the fog probability used to create the fog probability cloud objects involves calculating the 11 μm BT spatial uniformity of a 3x3 pixel box around each pixel. While this works well for large areas of fog/low cloud, small fog areas can appear non-uniform in temperature due to their size and are usually given a lower probability. Although the 3x3 pixel spatial uniformity may not work for small fog areas the overall spatial uniformity of the cloud object is relevant. The temperature throughout the cloud object should be uniform if fog/low stratus clouds are present, even small-scale fog events such as valley fog that may be several pixels long but only a pixel or two wide. After manually analyzing several scenes it was determined that as long as 11 μm BT standard deviation for the entire object was less than 0.2 K the object could be considered to contain fog/low cloud. If this threshold was not met the entire object was removed from the final fog mask.

1.11.2.4.1.2.4 Standard Deviation of the 3.9/0.65 μm Reflectance Ratio

This is the same test used for the fog probability cloud objects described in section 1.11.2.4.1.1.4. The only difference is the threshold that was chosen. Because the surface temperature bias cloud objects are usually smaller, fewer pixels are used for the calculation of the standard deviation, which can tend to lead to smaller overall values. For this reason a slightly tighter threshold of 0.2 was chosen after the manual analysis of several GOES-12 scenes. As long as the standard deviation of the reflectance ratio for a given object is less than 0.2 the object is retained. If not, the entire object is removed from the final fog/low cloud mask.

1.11.2.4.2 *Nighttime Fog Decision Logic*

Only one set of the cloud objects is created at night and, therefore, only one set of statistics is needed to analyze the cloud objects. Section 1.11.2.3.4.2 summarizes the statistics used to filter out objects that do not meet the fog/low cloud criteria. This section describes why each statistic was chosen and how the thresholds were determined.

1.11.2.4.2.1 Fog Decision Logic for Fog Probability Cloud Objects

This section describes the cloud object statistics used to analyze the nighttime fog probability cloud objects.

1.11.2.4.2.1.1 11 μm BT Spatial Uniformity CDF

One of the characteristics of fog/low stratus clouds is that they are spatially homogeneous in temperature. The nighttime 11 μm BT spatially uniformity statistic is used to remove clouds that are not spatially uniform in temperature (e.g., stratocumulus clouds) that do not pose a hazard to aviation. This is done using the CDF of the standard deviation of the 3x3 pixel 11 μm brightness temperatures centered on each pixel in the cloud object. Objects made up of pixels containing fog/low stratus cloud should contain mostly low standard deviation values, meaning they are spatially uniform, except near the edges where the values may be higher due to the mixture of non-fog/low cloud pixels with fog/low cloud pixels. Figure 21 contains the CDF's of the 11 μm BT spatial uniformity for several manually picked areas of both non-fog/low cloud and fog/low cloud that would likely be made into objects due to their ems(3.9μm) and surface temperature bias. Surface observations of ceiling were used to determine if fog/low cloud were reported for each area.

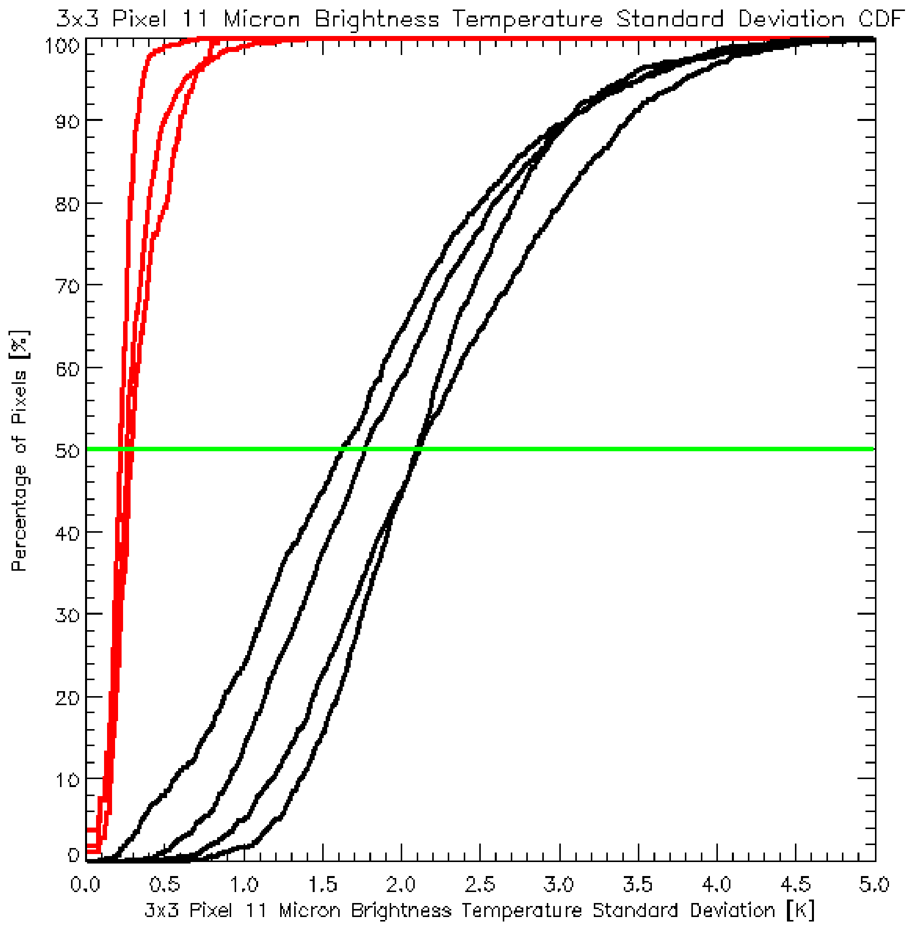


Figure 21 - CDF of the 3x3 pixel 11 µm BT spatial uniformity for several manually chosen areas of fog/low cloud (red) and non-fog/low cloud (black). The green line represents where 50% of the pixels in the distribution have a spatial uniformity below the value it intersects the CDF.

Based on the CDF's such as the ones from Figure 21, a threshold was chosen that distinguishes objects containing fog/low cloud from those that do not. The threshold chosen was 50% of the pixels in a given object must have a 3x3 pixel 11 µm spatial uniformity of less than 0.5 K. If this threshold is exceeded the entire object is removed from the final fog mask.

1.11.2.4.2.1.2 Surface Temperature Bias CDF

Although the surface temperature bias was used for the LUT to obtain the fog probability used to create the cloud object, relatively high probabilities (> 40%) can be assigned to pixels even with large surface temperature biases. The distribution of the surface temperature bias is used to remove cloud objects that most likely have ceilings too high to be considered fog/low stratus cloud. Figure 22 contains the CDF's of the surface temperature bias for several manually picked areas that would likely be made into objects due to their 3.9 μm pseudo-emissivity and surface temperature bias. Surface observations of ceiling were used to determine if fog/low cloud were reported for each distribution.

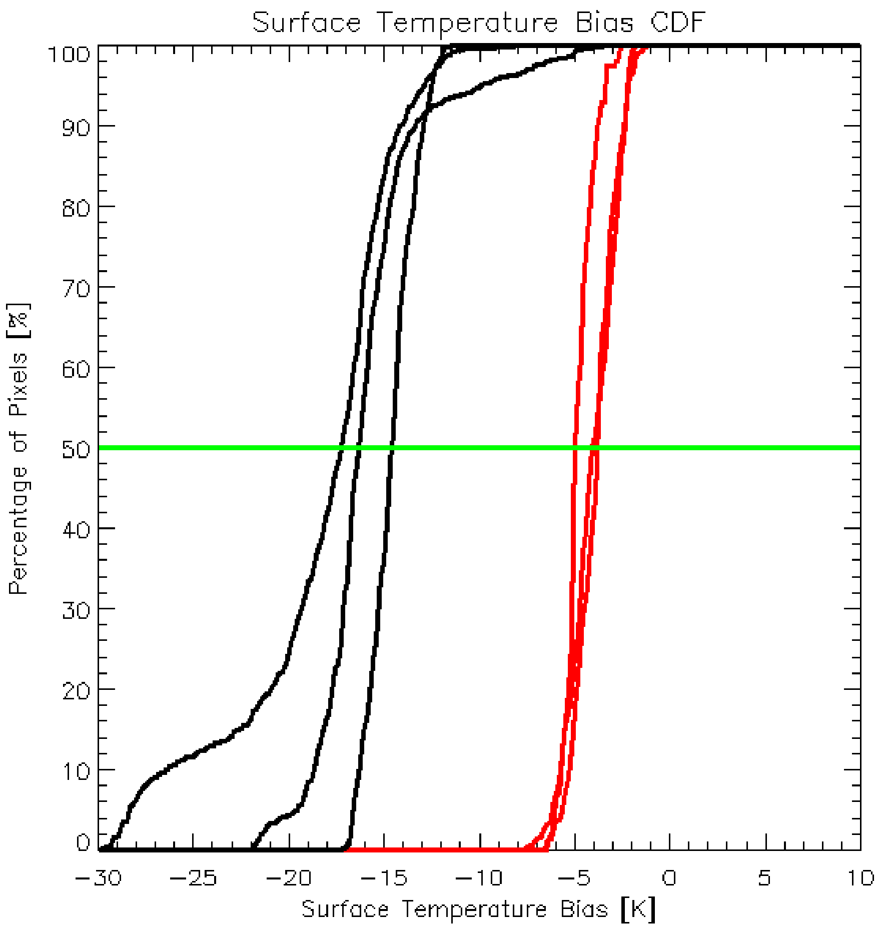


Figure 22 - CDF of the surface temperature bias for several manually chosen areas of nighttime fog/low cloud (red) and non-fog/low cloud (black). The green line represents where 50% of the pixels in the distribution have a surface temperature bias above the value it intersects the CDF.

Based on the CDF's, a threshold was chosen that distinguishes objects containing fog/low cloud from those that do not. The threshold chosen was 50% of the pixels in a given object must have a surface temperature bias greater than -15 K. If this threshold is not reached the entire object is removed from the final fog mask.

1.11.2.5 Determining Fog Depth

The fog algorithm uses separate approaches for estimating fog geometrical thickness during the day and night. The daytime method uses the liquid water path (LWP) calculated from the daytime microphysical properties algorithm while the nighttime method is based on the work of Ellrod (1995). Both are explained in the following sections.

1.11.2.5.1 *Daytime Fog Depth*

The daytime fog/low stratus thickness product utilizes the calculated LWP from the daytime cloud microphysical properties algorithm and an assumed value for the liquid water content (LWC). Using the optical properties of aerosols and clouds and the fog size distribution model from Tampieri and Tomasi (1976), Hess et al. (1998) determined that a typical LWC of fog is 0.06 g/m^3. Hess et al. (1998) found that the LWC of marine and continental stratus clouds was around 0.3 g/m^3. It appears that the majority of the pixels that are flagged by the fog detection algorithm are stratus clouds, so for simplicity, a LWC of 0.3 g/m^3 is currently used for all daytime pixels flagged as fog/low stratus by the fog mask. The cloud geometrical thickness (m) if computed by dividing the LWP (g/m^2) by the LWC (g/m^3). Figure 23 shows a daytime GOES-12 scene with the corresponding fog/low cloud thickness result.

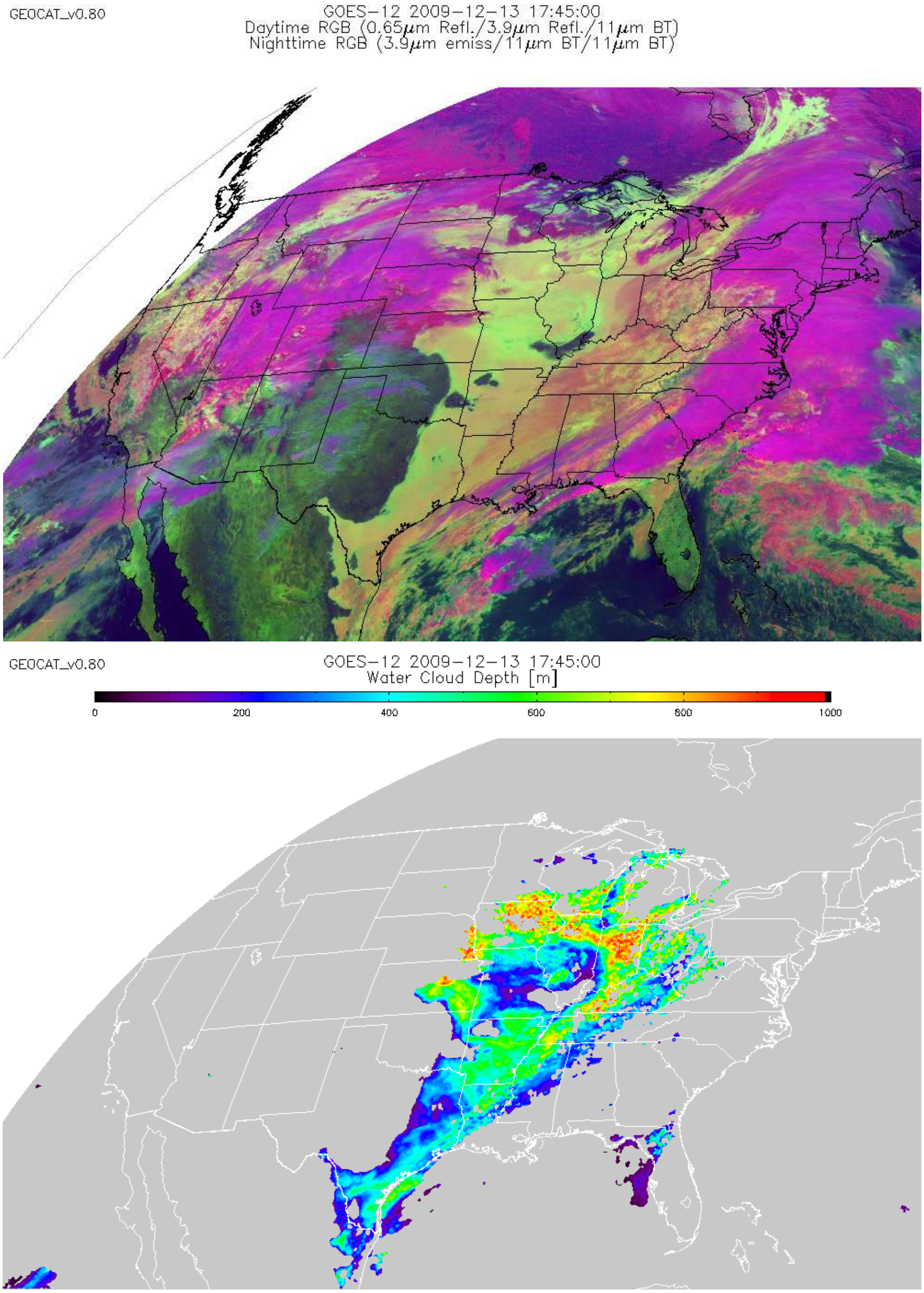


Figure 23 - False color image (top) using the 0.65, 3.9 and 11 μm channels for GOES-12 over CONUS on December 13, 2009 at 17:45 UTC along with the fog/low stratus detection and thickness output (bottom) from the ABI fog algorithm.

1.11.2.5.2 *Nighttime Fog Depth*

Currently the nighttime retrieval of LWP is not adequate to determine the fog depth. Previously, Ellrod (1995) determined that there is a correlation between nighttime 11-3.9 μm brightness temperature differences (BTD's) and fog thickness. Building upon this concept, the ems(3.9μm) is used in lieu of the BTD because it takes into account viewing geometry and atmospheric water vapor absorption. Comparing fog thickness measured using ground-based instruments from the San Francisco Bay area, a linear relationship was found between the ems(3.9μm) and fog/low cloud thickness (Figure 24). The fog thickness calculated using the ground-based instruments came from subtracting the cloud base measured from ceilometers from the fog top height measured by a SOnic Detection And Ranging (SODAR) system.

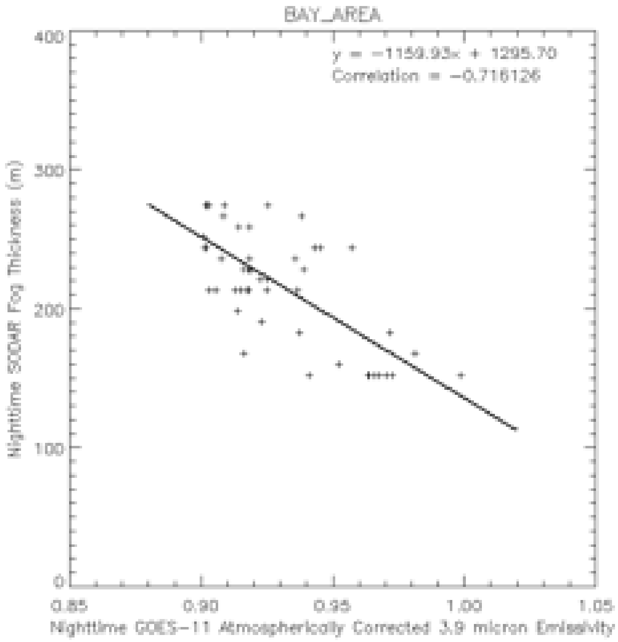


Figure 24 - Scatter plot of fog thickness measured by ground-based SODAR and ceiling heights vs. collocated 3.9 μm pseudo-emissivity from GOES-12.

By performing a linear regression to the data in Figure 24 a linear equation was found that fits the trend of the data with a correlation coefficient of ~0.72. This equation is used to calculate the fog thickness for all nighttime pixels flagged as fog/low cloud by the ABI fog algorithm. Figure 25 shows a nighttime scene with the fog thickness regression equation applied to the 3.9 μm pseudo-emissivity channel from GOES-12 where the ABI fog algorithm detected fog/low cloud.

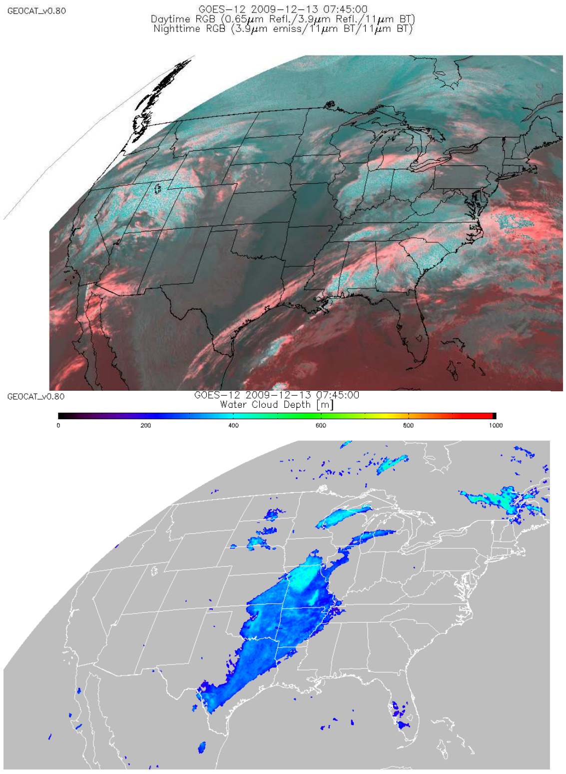
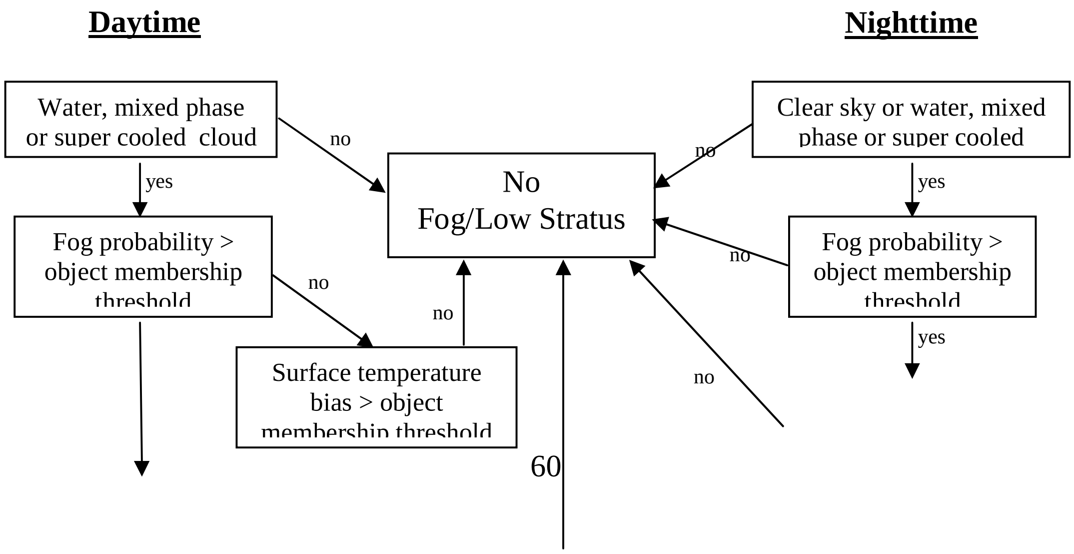


Figure 25 - False color image (left) using the 3.9, 11 and 11 µm channels for GOES-12 over CONUS on December 13, 2009 at 7:45 UTC along with the fog/low stratus detection and thickness output (right) from the ABI fog algorithm.

1.12 Mathematical Description

The various tests that comprise the fog algorithm were described in the previous section. The final fog mask is determined solely by the yes/no decisions of those tests. The current logic to derive the final fog mask is shown in Figure 26. In order for a pixel to be flagged as having fog/low stratus, all tests (depending on whether it is day or night) must be passed



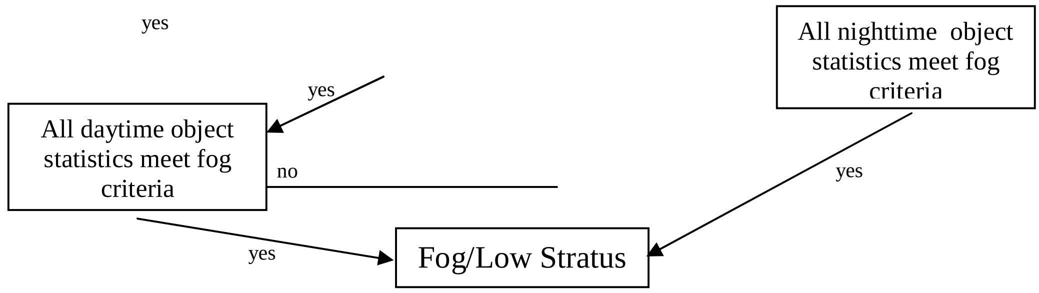


Figure 26 - Schematic illustration of the logic employed to derive the fog/low stratus mask from the individual test results.

The methods used to estimate the fog/cloud thickness were described in section 3.4.1.2. For the daytime calculation of fog/low stratus thickness when the solar zenith angle is less than 70°, the following equation was used:

$$\Delta Z = LWP/LWC$$

where ΔZ is the thickness, LWP is the liquid water path and LWC is the liquid water content. Currently, calculating fog/low status thickness in the terminator region (70° < solar zenith angle < 90°) is not possible.

The nighttime calculation of fog/low stratus thickness is performed using the following linear regression-based relationship between the 3.9 μm pseudo-emissivity and fog depth determined by ground-based instruments:

$$\Delta Z = A[ems(3.9\ \mu m)] + B$$

where ΔZ is the thickness, ems(3.9 μm) is the 3.9 μm pseudo-emissivity and A and B are regression constants calculated to be -1159.93 and 1295.70 respectively (see Figure 24). This method is analogous to the commonly known relationship used by Ellrod (1995) with the substitution of the 3.9 μm pseudo-emissivity for the 3.9 – 11 μm brightness temperature difference.

1.12.1 Algorithm Output

The final output of the fog/low cloud algorithm and description of their meaning is given below.

Fog/Low Stratus Mask Value	Description
Binary Fog Mask	Pixels that passed all tests for fog/low stratus (0=NO, 1=YES)
Fog Thickness	Thickness of fog/low cloud layer in meters

Quality Flags	See Table 7
Product Quality	See Table 8
Metadata	See Table 9

Table 6 - Table describing the fog/low stratus detection output from the ABI fog algorithm.

1.12.1.1 Quality Flags (QF)

A complete and self-contained description of the GOES-R ABI fog/low cloud quality flag output is listed in Table 7.

Bit(s)	QF Description	Bit Interpretation
1	**Fog/low cloud probability quality flag –** the product quality will be dependent on the fog probability assigned to each pixel. Four levels of quality, with 0 being the highest and 3 being the lowest will be designated.	0 = 75% - 100% (high) 1 = 50% - 75% 2 = 25% - 50% 3 = 0% - 25% (low)
2	**Multi-layered cloud quality flag –** this will be set to "low quality" if multi-layered clouds are detected by the GOES-R cloud phase algorithm as fog may be present but may not be detected	0 = multi-layered clouds not detected 1 = multi-layered clouds are detected
3	**Cloud phase quality flag –** this will bet set to "low quality" if ice clouds are detected by the GOES-R cloud phase algorithm because the fog/low cloud algorithm will not be run	0 = ice clouds not detected 1 = ice clouds are detected
4	**Freezing fog flag –** this flag will represent whether each pixel containing fog/low cloud has a temperature below freezing (0 K) indicating the possibility of freezing fog	0 = temperature of fog/low cloud pixel is at or below 0 K 1 = temperature of fog/low cloud pixel is above 0 K
5	**Fog Depth quality flag –** this flag will indicate which pixels have solar zenith angles between 70° – 90°, where fog depth is not possible due to the lack of lwp or ems(3.9 μm) information	0 = pixel has solar zenith angle either < 70° or > 90° (fog depth available) 1 = pixel has solar zenith angle between 70° - 90° (fog depth NOT available)

Table 7 – A complete description of the fog/low cloud quality flag output is shown.

1.12.1.2 Product Quality Information (PQI)

A complete and self-contained description of the GOES-R ABI fog/low cloud Product Quality Information (PQI) output is listed in Table 8.

Bit(s)	PQI Description	Bit Interpretation
1	Pixel is geolocated and has valid spectral data	0 = FALSE 1 = TRUE
2	Pixel is a member of a fog/low cloud object	0 = FALSE 1 = TRUE
3	Pixel is considered a daylight pixel (solar zenith angle > 90°)	0 = FALSE 1 = TRUE
4	Pixel is located over land	0 = FALSE 1 = TRUE
5	Describes which surface emissivity bin each pixel uses for the fog probability LUT (bin 0 is for sfc emiss < 0.90, bin 1 is for sfc emiss ≥ 0.90)	0 = Bin 0 1 = Bin 1

Table 8 – A complete description of the fog/low cloud Product Quality Information (PQI) output is shown.

1.12.1.3 Product Metadata

A complete and self-contained description of the GOES-R ABI fog/low cloud metadata output is listed in Table 9.

Metadata Description
Number of fog eligible pixels (i.e., number of pixels given a fog probability from the LUT’s)
Fraction of pixels in scene detected as fog/low cloud
Mean fog depth from pixels detected as containing fog/low cloud
Standard deviation of fog depth from pixels detected as containing fog/low cloud

Table 9 – A complete description of the fog/low cloud metadata output is shown.

2 TEST DATA SETS AND OUTPUTS

2.1 Simulated/Proxy Input Data Sets

The data used to test the ABI fog/low stratus cloud algorithm consists of GOES-12 observations. The fog/low cloud algorithm is validated using surface observations for detection and surface observations and SODAR data for thickness. All of these data sets are described below.

2.1.1 GOES-12 Data

GOES-12 provides five spectral channels with a spatial resolution of 4km and provides spatial coverage of the full disk with a temporal resolution of 3 hours. Smaller CONUS and Northern Hemisphere domains are available every 15 minutes. GOES-12 provides the best source of data currently for testing and developing the ABI fog/low cloud algorithm due to the similarities in the spectral channels. Figure 27, shown below, is a full-disk GOES-12 image from 17:45 UTC on December 13, 2009. GOES-12 data are readily available from the University of Wisconsin Space Science and Engineering Center (SSEC) Data Center.

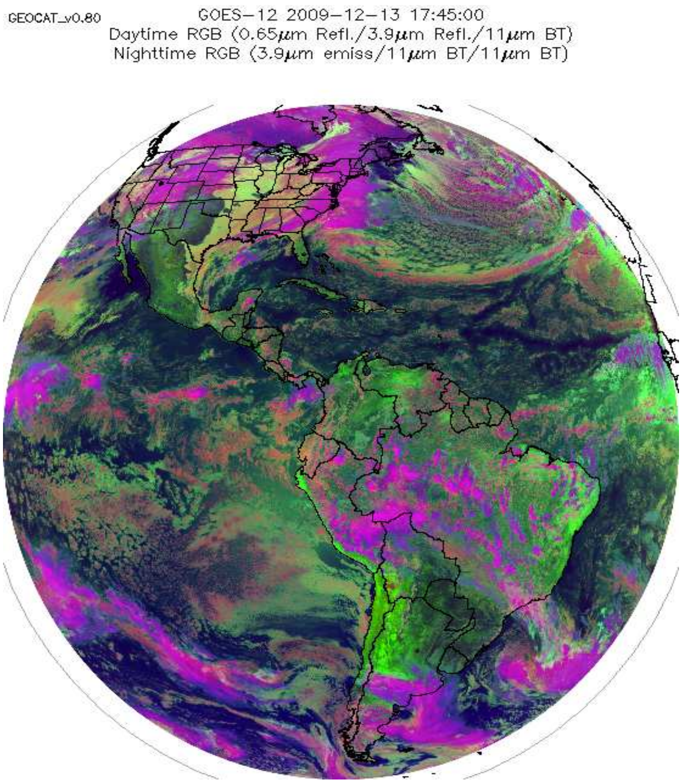


Figure 27 – GOES-12 RGB image from 17:45 UTC on December 13, 2009.

2.1.2 Surface Observations

Surface observations are received from both manned and automated ground stations all over the world. They provide accurate ground-based measurements of weather parameters such as temperature, pressure, weather conditions, etc., with relatively high temporal coverage (usually every hour, but varies by station). A useful surface observation parameter for validating fog/low cloud is the observed cloud ceiling. The most densely concentrated number of surface observations comes from the United States and Europe. Because of its position, GOES-12 does not provide information over Europe. For validation purposes surface observations over CONUS provide the greatest amount of data.

The surface observations over CONUS come from Automated Surface Observing System (ASOS) sites across the country. The ASOS program was created and is maintained by a joint effort between the National Weather Service (NWS), the Federal Aviation Administration (FAA) and Department of Defense (DOD). The cloud ceiling observations used to create the fog probability LUT's (see sections 1.11.2.2.1.1 and 1.11.2.2.2.1) and to validate the GOES-R fog/low cloud product are measured using a laser ceilometer. The valid range of the laser ceilometer at the ASOS stations is 100-12,000 ft with an accuracy of ±100 ft or 5% (whichever is greater). The product range and accuracy information was obtained from the ASOS User's Guide and ASOS User's Guide Appendices, which can be found at the NWS ASOS website (www.nws.noaa.gov/asos).

2.1.3 SODAR Data

The acoustic SODAR is an upwardly pointing parabolic antenna that emits an audible pulse whose return signal is proportional to the vertical gradient of air density. This gives it the capability of detecting the base of the atmospheric inversion, which defines the top of the stratus deck. Combining this data with the measured cloud ceiling from a ceilometer allows for the calculation of the geometric boundaries of low clouds.

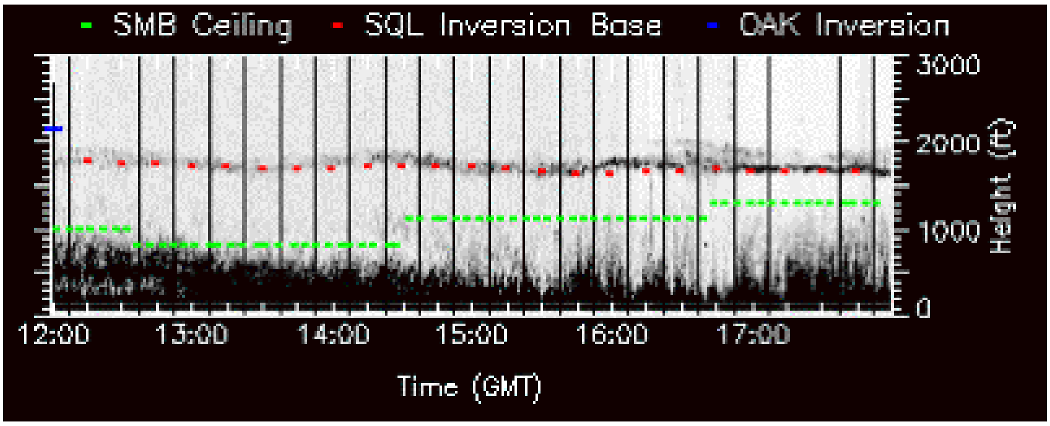
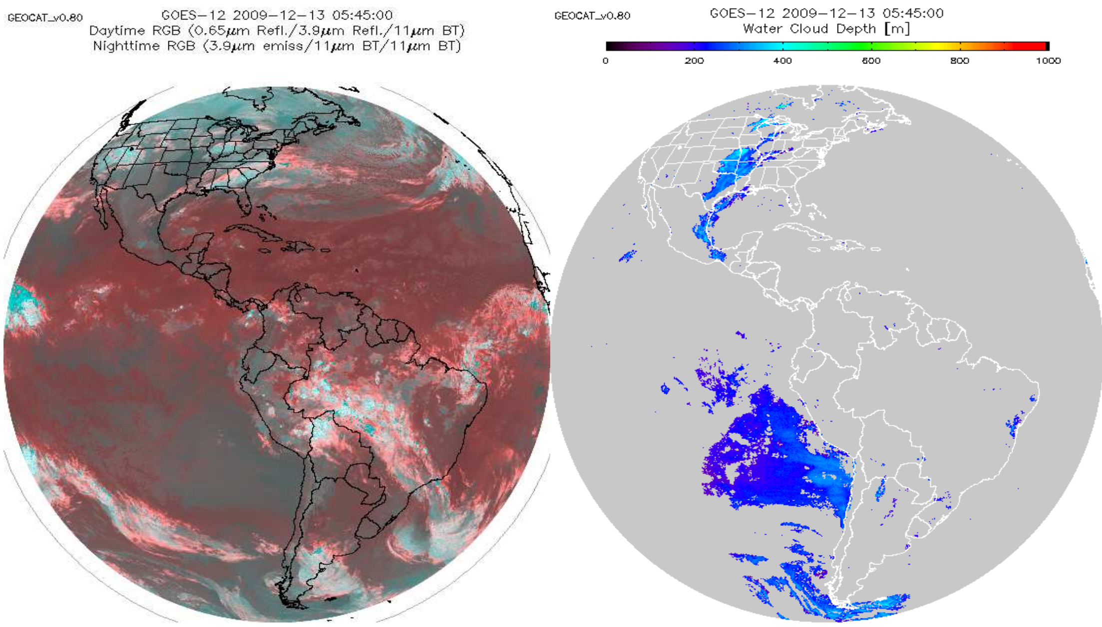


Figure 28 – An example of SODAR data combined with cloud ceiling. The red dashed line represents the base of the atmospheric inversion (i.e., stratus top) and the green dashed line represents the measured cloud ceiling. The difference between the two lines is the stratus deck thickness.

Unfortunately, SODAR data is only available at a small number of locations and not at every surface observation site. For the ABI fog/low cloud validation the SODAR data came from two sites around the San Francisco Bay Area courtesy of the NWS San Francisco Bay Area Forecast Office (Clark et al., 1997).

2.2 Output from Simulated/Proxy Inputs Data Sets

The ABI fog/low cloud algorithm was tested on several GOES-12 full disks. As an example, results from December 13, 2009 at 5:45 and 17:45 UTC are shown below. A more detailed zoomed in region over CONUS is also shown. Manual analysis of the results compared to false color images shows that areas of fog/low cloud are detected well. A more quantitative validation is shown in the next section.



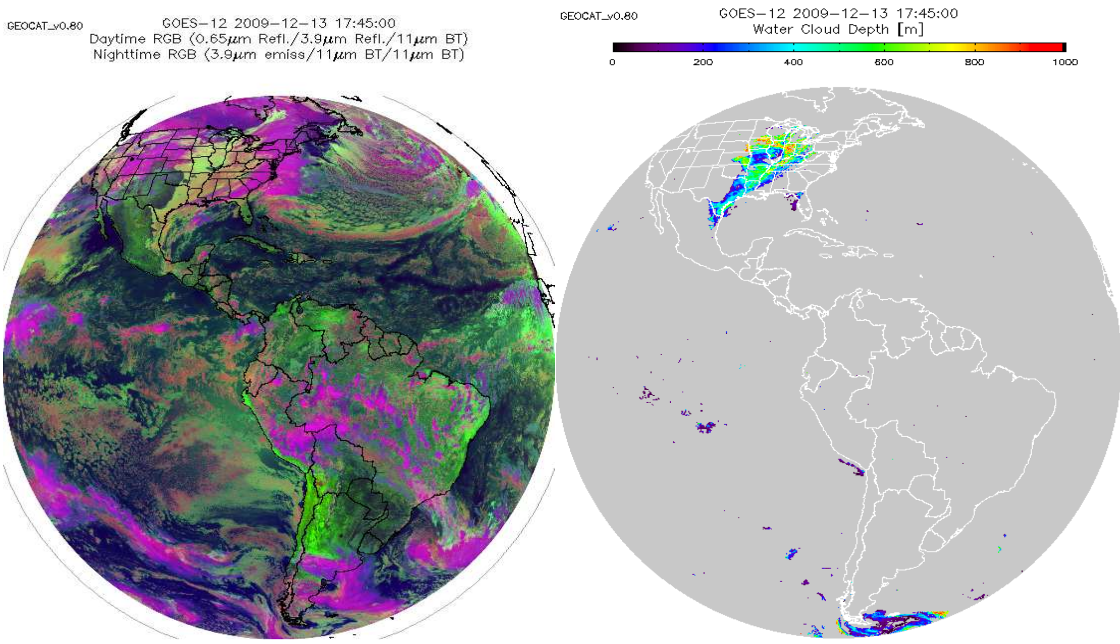
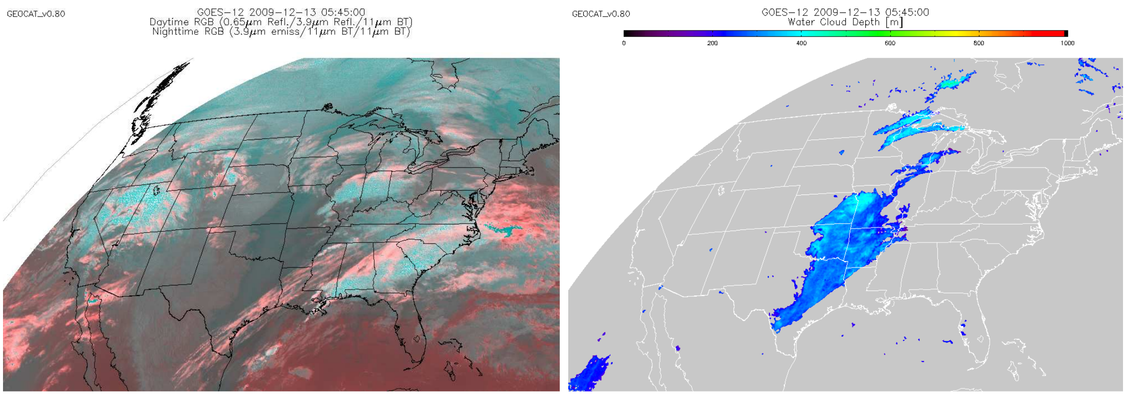


Figure 29 – Example results (using GOES-12) from the ABI fog/low cloud detection algorithm for December 13, 2009. The left side panels are RGB false color images for 5:45 UTC (top) and 17:45 UTC (bottom) from December 13, 2009. The panels on the right side show the corresponding fog/low cloud thickness results where the algorithm detected fog/low cloud.



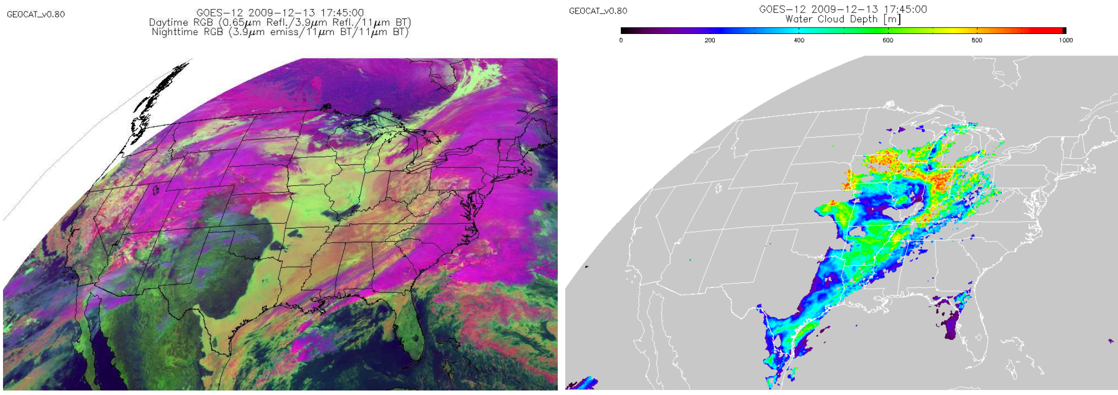


Figure 30 – A more detailed look at the fog/low cloud detection and thickness results shown in Figure 29 over CONUS.

2.2.1 Precisions and Accuracy Estimates

To estimate the precision and accuracy of the ABI fog/low cloud detection algorithm, measurements of cloud ceiling from surface observations were used. As previously mentioned, the GOES-R fog/low cloud detection product is designed to quantitatively identify clouds that produce IFR conditions (ceiling < 305 m). Surface observations of cloud ceiling depict areas that meet those conditions and can be collocated with the satellite pixels in order to validate the fog/low cloud product. Future validation efforts will focus on using a combination of surface observations with Cloud-Aerosol LIdar with Orthogonal Polarization (CALIOP) data (Vaughan et al. 2004). However, collocating CALIOP data with GOES-12 is difficult and currently not available. CALIOP provides unprecedented information on cloud vertical structure and horizontal location on a global scale, which can useful for depicting low stratus clouds.

To estimate the precision and accuracy of the ABI fog/low cloud thickness algorithm, comparisons to measured fog thicknesses using ground-based SODAR and ceilometer data were performed. The acoustic SODAR system allows the bottom of the atmospheric inversion to be detected, which corresponds to the top of the stratus layer overhead. The ceilometer data is used to find the base of the stratus layer. The thickness of the cloud layer is the height difference between the inversion level and the cloud ceiling and is used to validate the fog/low cloud thickness algorithm.

2.2.2 Error Budget

The ABI fog/low cloud detection algorithm was applied to GOES-12 and validated using surface observations of cloud ceiling as discussed in the previous section. The ABI fog/low cloud thickness algorithm was also applied to GOES-12 and validated using a combination of ground-based SODAR data and cloud ceiling.

2.2.2.1 Fog/Low Cloud Detection Error Budget

To validate the GOES-R fog/low cloud algorithm the Hanssen-Kuiper skill score (KSS), sometimes called the Hanssen-Kuiper discriminant was used. The KSS can be defined as the difference between the probability of detection (POD) and the false alarm rate (FAR) of a given set of events. The KSS has a range of -1.0 to 1.0, where 0.0 represents no skill. Negative values represent reversed forecasts and can be converted to positive skill simply be changing 'yes' detections to 'no' and vice versa. Table 10 is provided to show how the KSS is calculated.

Table 10 – The Hanssen-Kuiper Skill Score (KSS) visualized using the GOES-R fog/low cloud detection algorithm as an example.

fog/low cloud detected	*fog/low cloud observed by surface observation*	
	YES	**NO**
YES	h (hit)	f (false alarm)
NO	m (miss)	z (non-event)

The POD is defined as the number of fog/low cloud events properly detected divided by the total number of fog/low cloud events observed, or from Table 10 above:

$$POD = \frac{h}{h + m}$$

The FAR is defined as the number of fog/low cloud events falsely detected divided by the total number of events where fog/low cloud was not observed, or from Table 10:

$$FAR = \frac{f}{f + z}$$

The Hanssen-Kuiper skill score is defined as:

$$KSS = POD - FAR$$

The fog/low cloud algorithm is only designed to detect single layer liquid fog or low stratus clouds. In order to remove surface observations that have multi-layered or ice clouds overhead the ABI cloud type algorithm is used for screening. All collocated surface observations flagged by the cloud type algorithm as being multi-layered or ice are removed from the validation of the fog/low cloud product. Fog/low cloud detection results from December 13, 2009 and January 16, 2010 are shown in Table 11 and Table 12. There were more than 20,000 surface observation/GOES-12 match-ups for each of these days. According to the F&PS the accuracy specification for the fog/low cloud detection algorithm is 70% detection. At this stage of the algorithm development process

80% of the specification is to be achieved. The 80% specification for the fog/low cloud detection algorithm is 56% detection (KSS of 0.56 or higher).

Table 11 – ABI fog/low cloud detection validation statistics for December 13, 2009 including the probability of detection (POD), the false alarm rate (FAR) and the Hanssen-Kuiper skill score (KSS).

	# of Observations	POD	FAR	KSS
Day	7139	0.803	0.07	0.733
Night	14926	0.764	0.125	0.639
Combined	22065	0.779	0.11	0.67

Table 12 – Same as Table 11 but for January 16, 2010.

	# of Observations	POD	FAR	KSS
Day	5423	0.823	0.064	0.759
Night	19952	0.637	0.178	0.458
Combined	25375	0.664	0.151	0.513

Table 13 – Same as Table 11 but for both cases combined.

	# of Observations	POD	FAR	KSS
Day	12562	0.807	0.067	0.740
Night	34878	0.700	0.157	0.543
Combined	47440	0.731	0.134	0.597

The results from Table 13 show that the combined overall skill score for both the December 13, 2009 and January 16, 2010 scenes is 59.7%, which does meet the 80% F&PS accuracy requirement of 56%. However, it is apparent that the algorithm appears to perform better during the day. This is especially obvious for the January 16, 2010 case where the nighttime fog/low cloud detection does not meet the 80% specification. Although the validation results look poor, they may not be completely accurate. It was previously mentioned that the surface observations were initially screened using the ABI cloud type algorithm. However, if the cloud type algorithm misses multi-layered or ice clouds (especially thin cirrus) surface observations that should be excluded may negatively impact the validation results. An example of this is shown in Figure 31.

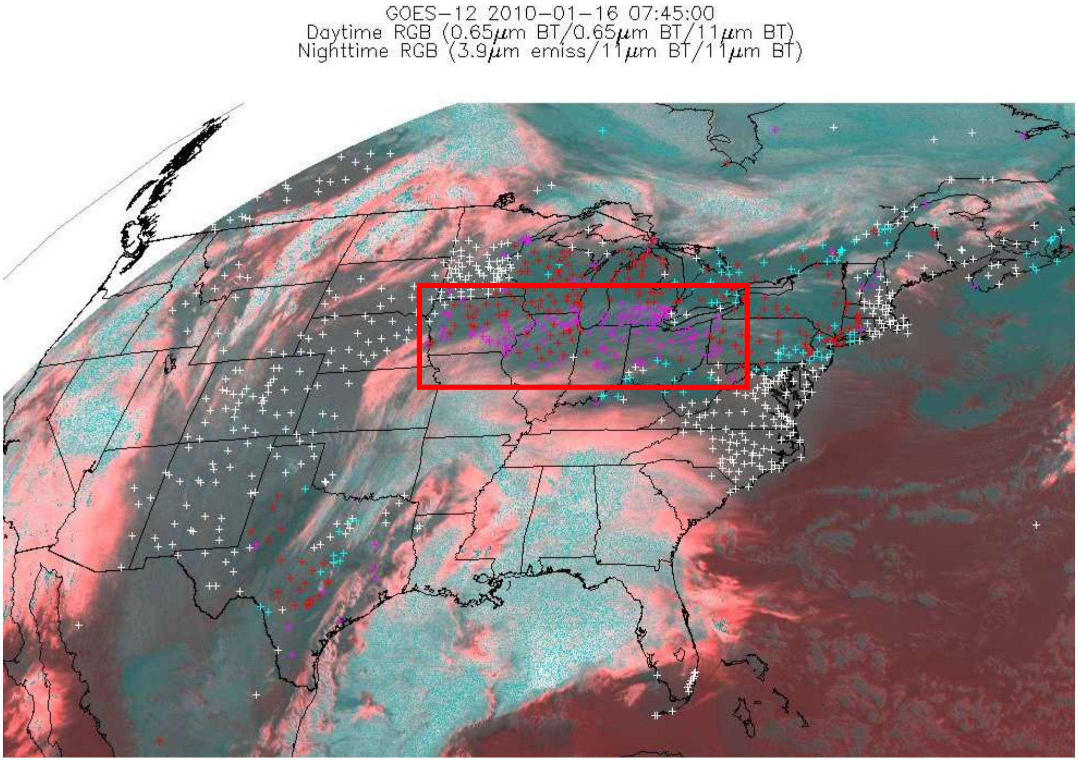


Figure 31 – GOES-12 RGB image for January 16, 2010 at 7:45 UTC with collocated surface observations (crosses). Collocated Surface observations flagged as either multi-layered or ice by the ABI cloud type algorithm have been screened out. White crosses represent surface observations reporting non-IFR conditions where fog/low cloud is not detected by the ABI fog/low cloud algorithm. Cyan crosses represent observations reporting non-IFR conditions where fog/low cloud is detected. Red crosses are observations reporting IFR conditions where fog/low cloud is detected. Magenta crosses represent observations reporting IFR conditions where fog/low cloud is not detected.

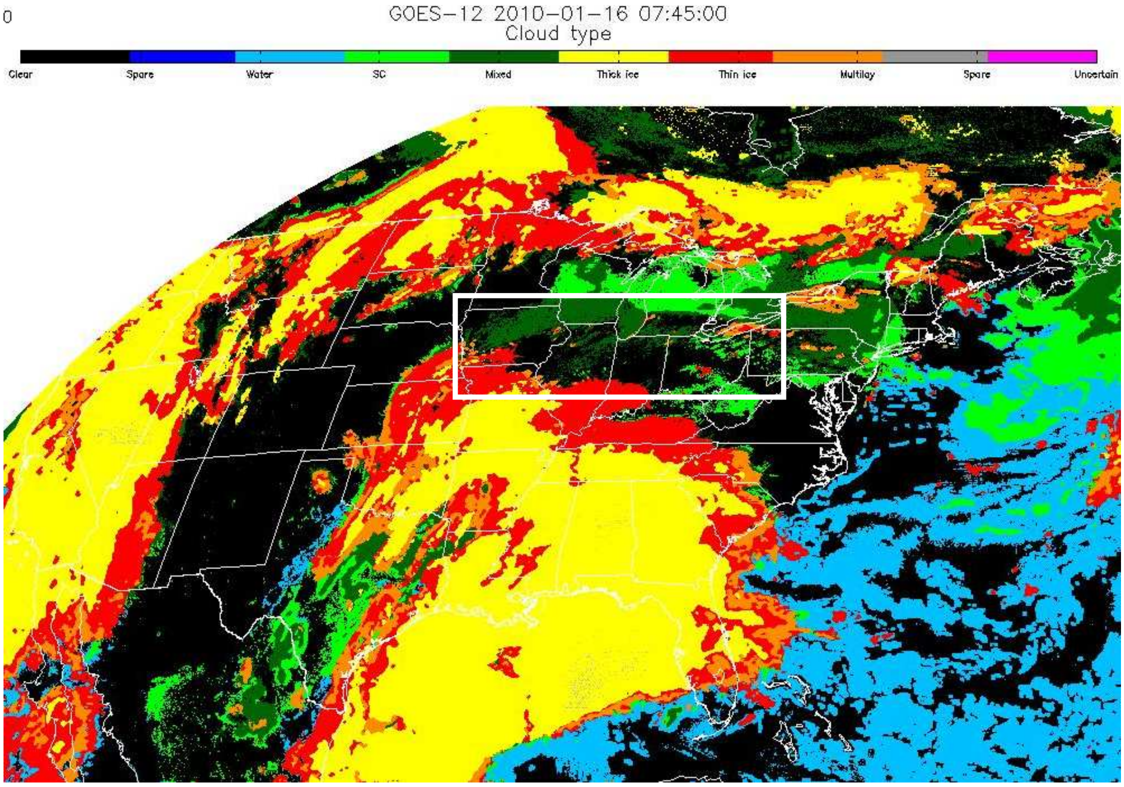


Figure 32 – The ABI cloud type algorithm for the same scene as Figure 31.

Looking at the red box in Figure 31 there were a large number of observations that reported IFR conditions where fog/low cloud was not detected. The Inclusion of those observations in the validation significantly reduces the probability of detection for this scene. A closer look reveals a very thin cirrus cloud layer over the area that is not detected by the ABI cloud type algorithm shown in the white box in Figure 32. The ABI cloud type algorithm does not always perform as well on GOES-12 data due to the lack of spectral channels needed for it to run at its full capability. The ABI fog/low cloud algorithm is not responsible for detection in this case since the radiometric signal from the cirrus cloud interferes with the signal from the underlying fog/low cloud. For this reason there must be further screening of the observations so they are not used for validation.

In order to remove observations that were not correctly screened out using the ABI cloud type algorithm, observations can be screened again using the radiometric surface temperature bias at their locations. As previously mentioned higher, colder clouds usually return a lower retrieved surface temperature, which leads to a higher radiometric surface temperature bias. This information can be used to remove observations that go unscreened by the cloud type algorithm but are located under multi-layered or thin ice clouds that make it impossible for the ABI fog/low cloud algorithm to detect properly. To see how this affects the validation results several levels of screening using different thresholds for radiometric surface temperature bias were performed. When only observations with biases greater than -15 K were used, the results were very similar to those seen in Table 12. However, as the observations were further-screened by increasing the radiometric surface temperature bias threshold, the skill scores raised significantly. The results from the January 16, 2010 case are shown in Figure 33.

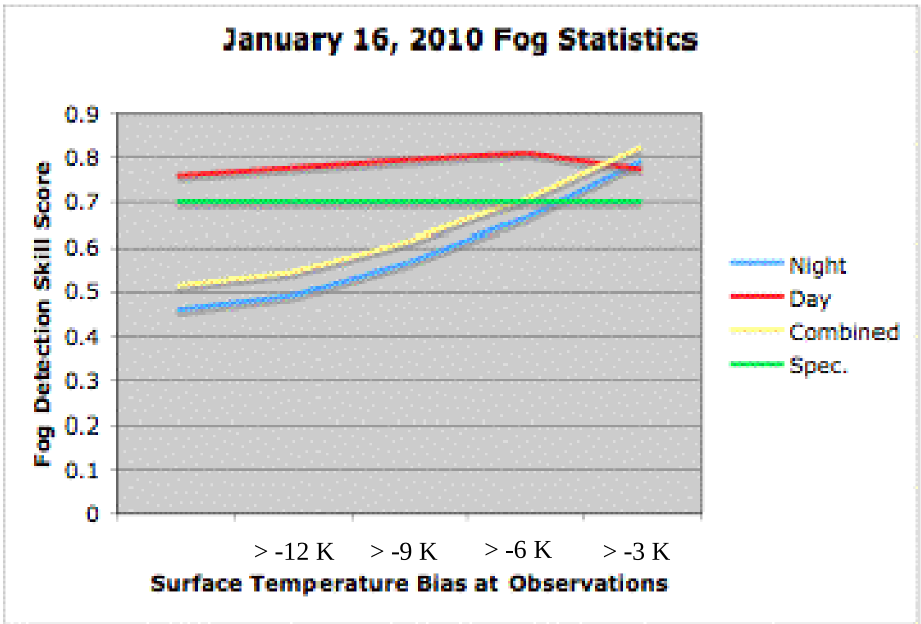


Figure 33 – ABI fog/low cloud detection validation skill scores using different thresholds of radiometric surface temperature bias to screen the surface observations. The green line represents the 100% F&PS fog/low cloud detection specification. The far left side of the curves represent the skill scores during the day, night and both combined, calculated using only surface observations with surface temperature biases > -15 K. The far right side of the curves represent the skill scores calculated using only observations with surface temperature biases > -3 K.

Shown in Figure 33, as the surface observations were screened using smaller radiometric surface temperature bias thresholds the resulting skill score rapidly improved. This occurs because the observations under the cirrus shield that made it through the cloud type screening shown in Figure 31 were removed, thus raising the probability of detection and overall skill score. When a threshold of -6 K was imposed the skill score increased to ~0.7, right around the 100% F&PS specification of 70%. It is clear that further screening other than using just the cloud type is necessary in order to remove surface observations that should not be included in the validation. It is shown that it can be difficult to validate the fog/low cloud algorithm using surface observations alone. Combining them with CALIOP data for validation will be a better option in the future.

2.2.2.2 Fog/Low Cloud Thickness Error Budget

Data from two stations in the San Francisco Bay Area were used to validate the ABI fog/low cloud algorithm. Fog thicknesses were calculated manually from several single-layer low cloud events like the one shown in Figure 28. Due to the lack of SODAR stations and the difficulty in manually finding single-layered fog events over such a small area, a large validation data set was not available. With the limited number of validation points that were obtained, an initial estimation of the accuracy of the fog/low cloud thickness algorithm was calculated. The F&PS requires the fog/low cloud thickness be detected within 500 m. Results gathered using SODAR data from several scenes are shown in Figure 34.

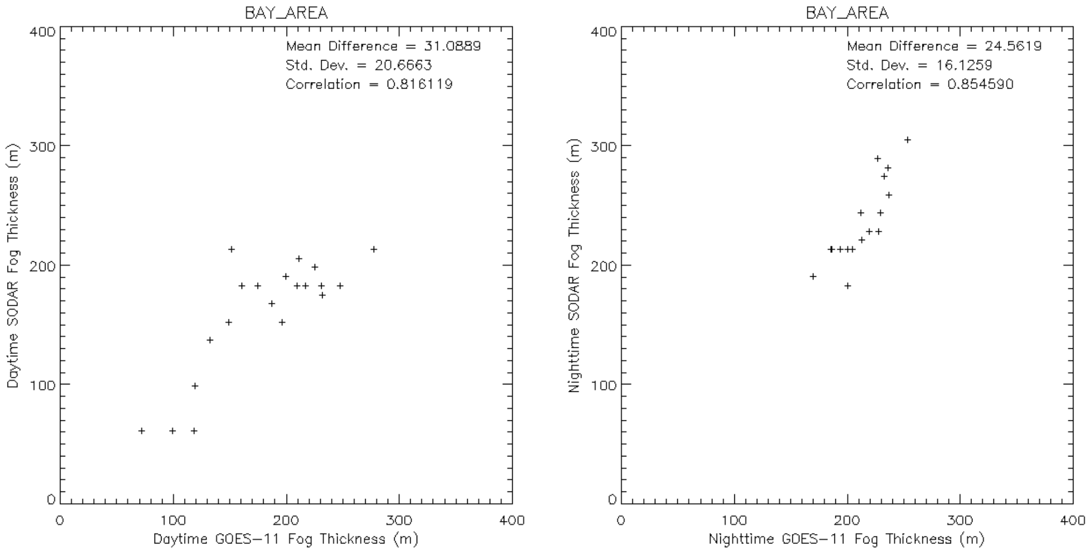


Figure 34 – Scatter plot comparing measured fog thicknesses using SODAR and ceiling data with thicknesses output from the ABI fog/low cloud thickness algorithm for both day (left panel) and night (right panel).

Initial performance estimates indicate that the 500 m accuracy will be readily achieved with a daytime bias of about 31 m and a nighttime bias of around 25 m. The strong correlations indicate that the spatial and temporal patterns are useful. Further validation will be needed in the future. The addition of CALIOP data may also prove to be useful for validation once the issue of collocating the data with GOES-12 is resolved.

3 PRACTICAL CONSIDERATIONS

3.1 Numerical Computation Considerations

The fog algorithm is implemented sequentially. Because it relies on the results of other cloud algorithms, the cloud mask, cloud phase and daytime optical properties must be run before the fog algorithm. In addition, the necessary RTM and NWP calculations also need to be processed and fed into the fog algorithm. The fog algorithm currently uses 6-hr forecasts. However, if these are not available, up to 24-hr forecasts can be utilized. All tests are applied before the final fog/low stratus mask and thickness are determined.

3.2 Programming and Procedural Considerations

The fog algorithm is, for the most part, a pixel-by-pixel algorithm. However, a spatial uniformity filter is currently used to reduce noise by taking into account the surrounding pixels.

3.3 Quality Assessment and Diagnostics

The following procedures are recommended for diagnosing the performance of the fog algorithm.

- Periodically image the fog mask and compare it to true color images to ensure proper areas are being correctly masked with minimal false detection.
- Continue to validate the fog algorithm using CALIPSO and surface observations.

3.4 Exception Handling

The fog algorithm currently checks the validity of all channels before running. If any channels are unavailable, the algorithm will still run disregarding tests reliant on those channels. The fog algorithm also expects the main processing framework to flag any pixels with missing geolocation or viewing geometry information.

3.5 Algorithm Validation

Currently surface observations are used to validate the fog/low cloud detection algorithm. In the future, surface observations of cloud ceiling will be combined with cloud top height derived from space borne lidar will serve as the main source of validation data for both the pre-launch and post-launch periods. For fog/low cloud thickness, ground-based measurements of cloud thickness using ceiling height and SODAR data are used as the main source of validation. A more extensive validation plan for the fog/low cloud algorithm will be created at a later date.

4 ASSUMPTIONS AND LIMITATIONS

The following sections describe the current limitations and assumptions in the current version of the ABI fog/low cloud algorithm.

4.1 Performance

The following assumptions have been made in developing and estimating the performance of the fog/low cloud algorithm. The following list contains the current assumptions (numbered) and proposed mitigation strategies (lettered).

1. NWP data of comparable or superior quality to the current 6 hourly GFS forecasts are available.
    a. Use longer-range GFS forecasts or switch to another NWP source – ECMWF

2. All of the static ancillary data are available at the pixel level.
    a. Reduce the spatial resolution of the surface emissivity and land mask

3. The processing system allows for processing of multiple scan lines at once for application of important spatial analysis techniques.
    a. No mitigation is possible

4. A more robust assumption of the LWC is necessary for daytime fog thickness calculation.
    a. Create a variable assumption for LWC depending on whether the algorithm detects fog or low stratus.

In addition, the clear sky radiance calculations are prone to large errors, especially near coastlines, in mountainous regions, snow/ice field edges, and atmospheric frontal zones, where the NWP surface temperature and atmospheric profiles are less accurate. Improvements in NWP fields should lead to additional improvements in the ABI fog/low cloud products.

4.2 Assumed Sensor Performance

We assume the sensor will meet its current specifications. However, the fog/low cloud algorithm will be dependent on the following instrumental characteristics.

- The fog/low cloud algorithm is dependent on several other cloud algorithms (see section 1.9); therefore any issues that degrade those algorithms may also affect the fog/low cloud algorithm. An example is how the amount of striping in the data may affect spatial uniformity tests in the other cloud algorithms leading to issues absorbed by the fog/low cloud algorithm.
- Unknown spectral shifts in some channels will cause biases in the clear-sky RTM calculations that may impact the ability to accurately calculate the surface temperature bias relied upon in the fog algorithm.

4.3 Pre-Planned Product Improvements

While development of the ABI fog/low cloud algorithm continues, we expect in the coming years to focus on the following issue.

4.3.1 Additional Capability to Run On SEVIRI

Due to wider 3.9 µm channel window on SEVIRI, the current nighttime LUT's used for the ABI and GOES-12 are not applicable. In order to use the ABI fog/low cloud algorithm on SEVIRI new LUT's will have to be created.

4.3.2 Terminator Temporal Test

Fog/low cloud detection is difficult in the daytime terminator region due to high solar zenith angles. A temporal test will be beneficial in keeping areas of fog/low cloud detected at night near the terminator into the terminator region where the daytime fog/low cloud algorithm may not detect them until solar zenith angles are decreased.

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